THE UNIVERSITY OF ALBERTA

GLACIAL FLUTINGS NEAR ATHABASCA

by

© ROBERT CANFIELD FRESCHAUF

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Glacial Flutings near Athabasca", submitted by Robert Canfield Freschauf in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

North-south trending glacial flutings near Athabasca have been examined and found to be similar to a certain kind of small scale current ripple formed by fluid flow. The ripples were found to have been formed by a series of oppositely rotating, evenly spaced spiral vortices oriented parallel to flow. The similarity of form, orientation and wavelength suggests that the flutings may have been formed by a similar kind of motion in the basal ice layers.

To test this hypothesis till fabrics were taken across several fluting ridges throughout the field area. It was found that a systematic pattern of pebble orientations existed at fabric sites located at similar positions on different ridges. Pebble orientations along the flanks of the ridges were found to trend in towards the crest areas in a systematic "herring-bone" pattern. As deposits of basal till tend to illustrate pebble orientations parallel to the line of ice movement it is inferred that the basal ice above the fluting ridges at the time of their formation had components of movement oblique to the line of regional ice movement. It is believed that this secondary kind of ice motion, termed "composite flow", is similar to the spiral vortices that created the longitudinal current ripples.

Data taken from two traverses across fluting ridges and troughs were analyzed by spectral analysis to test for the possible existence of a wavelength across the flutings. It was found that an expected wavelength of 90-120 meters was nonexistent in the Athabasca fluting field. No acceptable wavelengths were found along either traverse.

Samples of till were mechanically analyzed and insignificant vari-

ations in the particle size distributions of the samples indicate that the properties of the subglacial material were not a factor in the localization of the fluting field near Athabasca.

ACKNOWLEDGEMENTS

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CHAPTER ONE

PREVIOUS STUDIES OF

DRUMLINS AND GLACIAL FLUTINGS

Introduction

Hypotheses proposed to explain the formation of glacigenic landforms are commonly controversial. Because such features are conspicuous in the landscape they have attracted many varied, intriguing and occasionally improbable explanations. Drumlins, drumlinoid features and glacial flutings are good examples of such features. This series of features represents a gradation in size and length from short, low mounds to elongated features several kilometers in length.

Form and Composition of Features

The term "drumlin" is of Gaelic origin and refers to a round or oval shaped hill that was formed beneath glacial ice. Drumlins exhibit a wide variety of form, the most common being that of an inverted spoon or cigar shape (Fig. 1). They are composed of a variety of materials, ranging from till and partly stratified drift to solid rock. The leading nose of the drumlin often exhibits a blunt form, as opposed to the tapering tail of the feature. A rock core or other massive feature is occasionally found beneath the nose of the drumlin.

Drumlinoid features are illustrated by those forms which deviate from the classic cigar or inverted spoon shape (Fig. 1). This deviation can be shown in many ways, the most common being a merging of adjacent forms or a shortening or lengthening of the drumlin shape (Chorley, 1959).

Glacial flutings represent features found at the elongated end of

COMPARISON OF DRUMLIN, DRUMLINOID AND FLUTE SHAPE

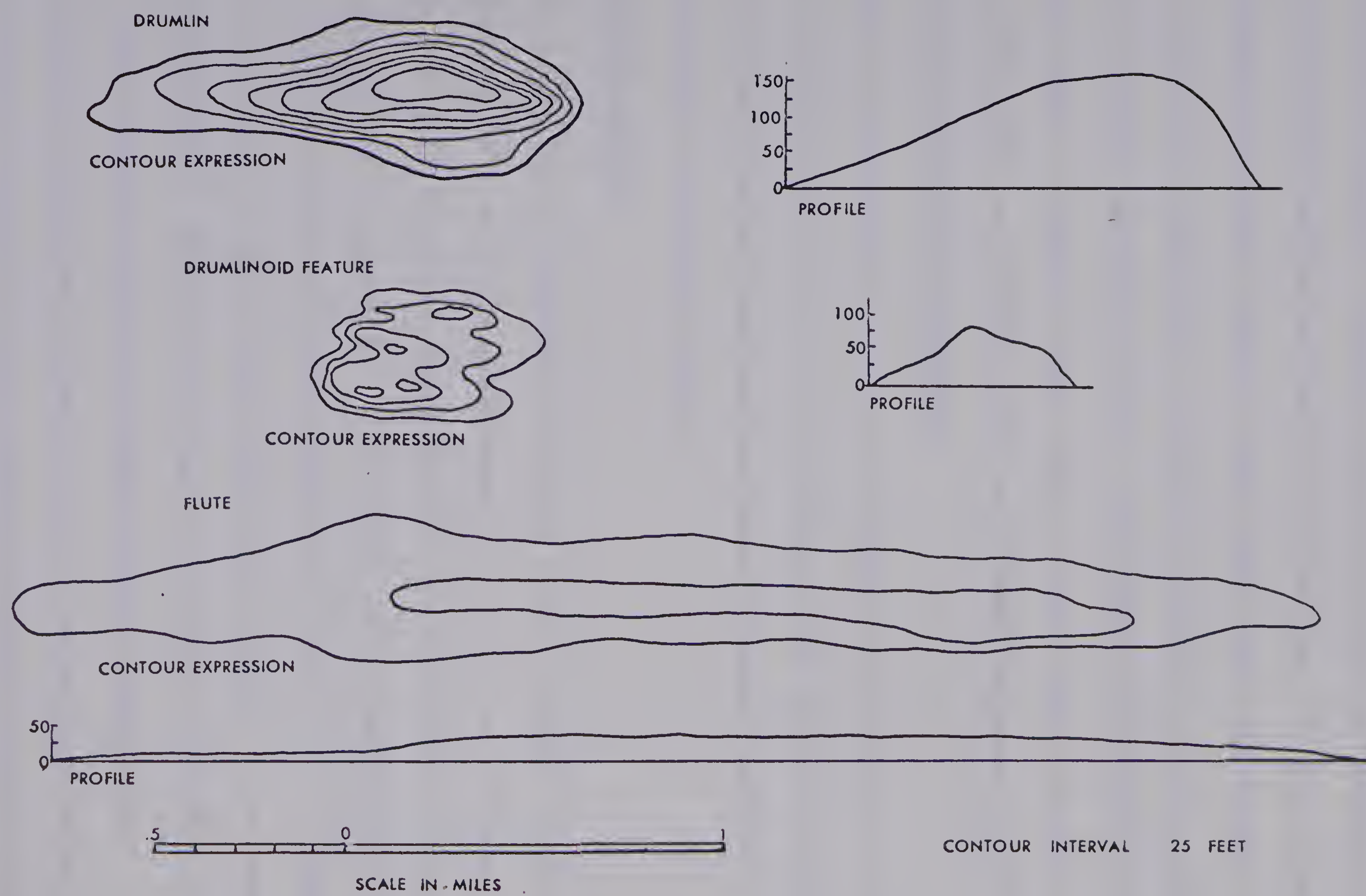


FIG. 1

the series (Fig. 1). Like drumlins, flutings rarely occur alone, but their physiographic distribution is even more limited than that of the drumlin form in general. Flutings seem to be limited to northwest and northcentral North America as examples of them have only been noted in the Northwest Territories (Smith, 1948), North Dakota and Montana (Lemke, 1958), Alberta and Saskatchewan (Gravenor and Meneley, 1958) and Manitoba (Wardlaw, Stauffer and Hoque, 1969). Very small scale flutings, however, have been noted in Montana (Dyson, 1952), Iceland (Hoppe and Schytt, 1953), Alberta (McPherson and Gardner, 1969) and Norway (Baranowski, 1970).

Theories for the Origin of Drumlins

Theories concerning the origin of drumlins can be grouped into two major categories, depositional and erosional. Each theory has found favor at various times and each has been shown to be more applicable to specific drumlin fields than others.

Depositional Theory

The basis for the depositional theory is that drumlins are formed by a "plastering on", or progressive deposition of till in localized areas. Exactly what initiates this deposition from the ice or how it is carried out still remains questionable. Alden (1905, 1911), Hollingworth (1931) and Charlesworth (1957) in general suggest that accretion, or deposition, begins at the base of an ice sheet when normal movement of the basal layers is interrupted. This interruption is presumed to be caused by a rock boss, frozen block of till or some other suitable obstruction.

Because ice cannot move freely around the obstacle, material is released from the debris-rich basal layers as the ice moves over and past the object. Accumulation of basal till (Boulton, 1970) is a process whereby basal layers of ice essentially stagnate due to the high content

of debris relative to ice. Irregular basal deposits are thus created and moulded into the drumlin shape.

The internal composition and structure of many drumlins, however, does not permit the use of the depositional theory. The materials comprising certain drumlins suggest that many are composed of till and stratified drift that existed prior to drumlin formation (Gravenor, 1953). These deposits include sand and gravel pockets that are often well sorted and stratified.

Erosional Theory

Erosional theories of Tarr (1894), Gravenor (1953) and Flint (1957) suggest that pre-existing drift is resculptured by ice advance and moulded into the drumlin shape. An irregular till plain or a moraine could conceivably be remoulded during ice advance into the drumlin shape. The fact that drumlins commonly occur up to thirty kilometers behind moraines suggests that they were created following an initial moraine forming stage or during a readvance stage which overrides the moraine (Gravenor, 1953; Smalley and Unwin, 1968).

During the formation of a moraine one would expect a certain amount of stratified drift to be present in the moraine. When stratified material is encountered in drumlins it more closely resembles morainal deposits rather than the kind found in kames (Gravenor, 1953).

Dilatant Properties of Till

Smalley and Unwin (1968) presented a unique theory for drumlin formation which considered more than having irregularly shaped obstacles remoulded into the drumlin shape. They believed that certain properties of the subglacial till and the stress levels present within the glacial ice are important factors permitting or prohibiting the formation of

drumlins.

Glacial till is an admixture of non-sorted sediment of various sizes deposited by glacial ice. The range of particle size of the till is believed by Smalley and Unwin to play an important role in the erosional process acting in the formation of drumlins. They suggested that a dilatant property, or resistance to shear stress, is present within the till and is directly related to the amount and size of boulders present within the till.

Dilatancy is a property of granular masses which can be measured and observed when the masses are subjected to increasing levels of stress, or compaction. When a body of sand, or in this instance, till, is subjected to pressure its natural close packing arrangement may be disturbed. The initial response of the material upon deformation is to expand, the distances between adjacent particles having been increased. By expanding, the mass is more easily deformed and, in the case of subglacial till, is easily eroded. The mass will resist deformation, however, and pack into a stable obstruction if the stress levels applied to it are insufficiently high or the packing arrangement is too tight. This obstruction is then moulded into the drumlin shape as the glacier advances.

Smalley and Unwin believed that the number and size of boulders within the till mass made it dilatant. Glacial ice overriding the till would exert pressure on the till that would be resisted owing to the packing arrangement of the boulders. Stress levels would be expected to increase as the ice front moved beyond the area in question. Drumlin fields commonly occur approximately thirty kilometers behind moraine areas, and it seems likely that if such a process operates during the formation of drumlins required stress levels of sufficient magnitude to

streamline masses are reached in these regions. If the stress levels exceed the required limits continuous deformation of the till would be expected and no drumlins would be formed.

Thixotropic Properties of Till

Thixotropicity, or the lack of resistance to shear, may also play an important role in the formation, or more specifically, the lack of formation of drumlins. Thixotropic substances are those which offer a minimal amount of resistance to deformation when subjected to even low shear stress levels. A highly clay-rich till with relatively few boulders present could conceivably be considered thixotropic, as any amount of shearing beneath glacial ice would totally deform the till and no drumlins would be produced. High clay content drumlins are rare (Gravenor, 1953) and a thixotropic property could help to explain their scant occurrence.

Orientation and Shape of Drumlins

It has long been known that drumlins are perhaps the most symmetrical and smooth-shaped of all glacial landforms. The smooth profiles in nearly all directions is quite conclusive evidence for their being an active ice feature. The orientation of drumlins is nearly always with the long axis parallel to the line of ice movement, with the blunt nose pointing into the direction of ice movement. The highest point along the long axis profile generally occurs approximately one third of the way back from the nose. A profile consistently asymmetric with the blunt end forward is, therefore, a response to the moulding process, regardless of an erosional or depositional origin.

The drumlin shape has been examined by Chorley (1959), Reed, Galvin and Miller (1962) and Heidenrich (1964). Chorley concluded that a

drumlin's streamlined form is one which presents the least amount of resistance to stress and creates the least amount of disturbance within the moving medium. Analogies have been drawn relating the drumlin shape to aircraft wings, fish and aquatic mammals, and even hen's eggs. All illustrate the same basic streamlining necessary for movement within each medium with the creation of a minimal amount of disturbance. In the case of drumlins, however, the ice is the moving medium and the drumlin shape is the response.

Fluting Shape

Glacial flutings are very similar to the drumlin form, except that they generally are extremely elongated features. Streamlining, or elongation with a smooth profile parallel to the line of ice movement, is the same as in drumlins. This indicates that they are also an active ice feature. The longitudinal profile of a fluting differs slightly from that of a drumlin because the maximum elevation of the crest is maintained for great distances which gives a very smooth, level appearance to the crest.

In a general sense flutings exist at two scales. Very small scale flutings have been described by Hoppe and Schytt (1953) on a ground moraine plain in front of a valley glacier in Icelend. Maximum sizes reached one meter in height and 100 meters long. The features observed had both positive and negative elements, i.e., stood above the general level of the ground moraine or were engraved into the till plain in the form of a giant groove.

Large scale flutings, such as those to which this study is concerned, have been described by Smith (1948), Gravenor and Meneley (1958) and Lemke (1958). The flutings ranged from two to three meters high and

several hundred meters long to twenty meters high and approximately twenty kilometers long. The flutings were formed in a variety of materials, ranging from unstratified drift to crystalline bedrock.

Theories for the Origin of Small Scale Flutings

Several theories have been advanced to account for the origin of small scale flutings. Two theories (Hoppe and Schytt, 1953; McPherson and Gardner, 1969) have been suggested which consider implements used in the formative process. A third theory (Baranowski, 1970) considers the possible role of permafrost in the basal material beneath the ice as the forming process. In all cases basal cavities, or crevasses, were thought to have been formed in the basal ice layers.

Hoppe and Schytt (1953) believed that basal cavities were formed when the ice moved past immovable obstructions imbedded in the ground moraine. Carol (1947) observed basal cavities down-glacier from roches moutonnées, and this same process is presumed to have occurred, although on a much smaller scale. McPherson and Gardner (1969) believed that splaying crevasses were formed in the ice near the glacier snout and that an unequal distribution of weight existed in this area. In both the above theories material was thought to have been squeezed up from the unfrozen ground moraine into the form of an elongate ridge.

Hoppe and Schytt (1953) also believed that large boulders may have been gouged into the ground moraine surface as the glacier advanced, subsequently leaving an elongated depression in the surface of the ground moraine. At the down-glacier ends of such features suitably sized boulders were found and were assumed to have been responsible for the gouging action. Where such boulders were absent from the depressions a frozen block of till which had subsequently disintegrated was thought

to have been responsible.

Baranowski (1970) partially rejected the above two theories on the grounds that the subglacial material was perennially frozen a certain distance behind the glacier tongue. Immediately preceding this zone unfrozen ground existed. At the contact of the frozen-unfrozen zone frost heaving was thought to occur due to a high content of water in the material. As the frost heaves occured the material was pushed up into the glacier base, creating a groove on the underside of the ice. As the ice moved beyond the heaves, small cavities would exist in the ice. Material subsequently was thought to have been squeezed up into the groove as the permafrost zone advanced with ice movement. Maintainance of the cavity as the ice advanced and movement of the permafrost zone were the two major requisites that had to be met. If the permafrost zone moved lower into the basal material or did not advance the formative process ceased.

Theories for the Origin of Large Scale Flutings

The feasibility of employing the above theories is minimal when large scale flutings are considered. The possibility of extended subglacial cavities beneath a thick ice sheet becomes hard to envisage as ice, flowing plastically, would not be able to maintain cavities for such lengths or of the required sizes. The concept of a large boulder or frozen block of till in the basal ice layers is dismissed also, as no such features have been found at the down-glacier ends of fluting fields. The above theories do not account for the preferred spacing of fluting ridges found in fluting fields of both sizes (Ray, 1935; Hoppe and Schytt, 1953; Gravenor and Meneley, 1958, Baranowski, 1970).

One must look elsewhere, therefore, to provide a suitable explana-

tion for the origin of flutings. If external implements or phenomena are to be eliminated, recourse must be had to some property within the glacial ice itself. Several articles concerning the origin of flutings and drumlins (Gravenor and Meneley, 1958; Aranow, 1959; Reed, Galvin and Miller, 1962; Andrews and King, 1968) have found it necessary to consider the possibility of some wave phenomena, motion, or lateral stress acting within the ice to account for the origin and placement of flutings and drumlins.

Suggestions to date concerning this motion are vague and noncommittal. To explain flutings Gravenor and Meneley (1958) suggested the existence of alternating bands of high and low pressure at the base of ice. Material beneath the high pressure bands would move obliquely to the low pressure bands to either side. The oblique motion, rather than directly perpendicular, was thought to have existed because the flutings were an active ice feature. The ice flow, therefore, was the resultant of a cross-stream and a down-stream vector component. Ridges, therefore, would be formed beneath the low pressure zones and the troughs beneath the high pressure zones.

Superficially this theory provides an explanation for the origin of flutings. Parallel bands of alternating high and low pressure were formed in the basal ice layers of actively moving ice. The basal material moved to the low pressure areas from beneath the high pressure areas. This theory, however, does not adequately explain the origin of such zones of high and low pressure or the mechanism of secondary ice flow which must have existed if material was to have moved obliquely with respect to the forward movement of the ice mass.

<u>Summary</u>

The formational theories of this series of features have been grouped into two major categories, erosional and depositional. The merits and characteristics of each theory must be weighed against the field evidence gathered for each specific drumlin field. It is perhaps too definitive to limit hypotheses to either a depositional or erosional origin, as no doubt a certain amount of erosion and deposition took place during the formation of all flutings and drumlins (Kupsch, 1955; Lemke, 1958).

Drumlins composed of till with pebble orientations consistently parallel to the long axis of the feature may be assumed to be mostly depositional in origin (Wright, 1957). The moulding process into the streamlined shape, however, obviously entailed a certain amount of erosion and a purely depositional hypothesis is incorrect.

The erosional theory is employed when the internal composition varies within the feature. Solid rock drumlins or those with heterogenous deposits are evaluated from the standpoint of the erosional theory, or some modification thereof (Gravenor, 1953; Smalley and Unwin, 1968).

Large scale flutings are somewhat anomalous features in that they seem to be limited to northwest and northcentral North America. Their elongate form and apparent wavelength between ridges suggests a different mechanism operated during their formation. Because they are similar in both of the above respects in both drift and crystalline bedrock flutings, the properties of the subglacial materials must play a relatively minor role in their formation.

Because flutings are an elongate feature and do not exhibit the exact form of drumlins, an extension, or perpetuation, of the formative

process is postulated. This perpetuation of the formative process is possibly related to lineated bands of high and low pressure in the basal ice layers. The material comprising the ridges would have originated in the trough areas and would have been transported obliquely from either side. This theory would indicate both an erosional and depositional origin.

CHAPTER TWO

DESCRIPTION OF THE STUDY AREA

Introduction

The area chosen for study is situated in central Alberta near the town of Athabasca (Fig. 2). The fluting field is nearly rectangular, being elongated in a NNE-SSW direction. The northern section and a portion of the western section of the field is bordered by the Athabasca River, which is incised approximately seventy meters beneath the till plain on which lay the field of flutings.

Although numerous other fluting fields exist in Alberta and Saskatchewan (Gravenor and Meneley, 1958) the Athabasca field was chosen because of its relative proximity to Edmonton (Fig. 3) and because of the relatively dense road network in the area. Numerous roadcuts were found to exist in the fluting field and their presence facilitated observation and sampling of the flute-crest materials.

In this study the terms flute and fluting will be considered as identical and will refer to both a ridge and the adjacent trough. When specification is needed the terms ridge or crest will be used. When reference is made to a depression the term trough will be used.

Bedrock Geology

The area is underlain by Upper Cretaceous shales and sandy shales of the La Biche Group (McCrossan and Glaister, 1964). These deposits represent marine and non-marine lagoonal and deltaic deposits of the Late Cretaceous seas. An unconsolidated, brown shale was the only exposure of bedrock seen in the field area and occurred immediately south of the

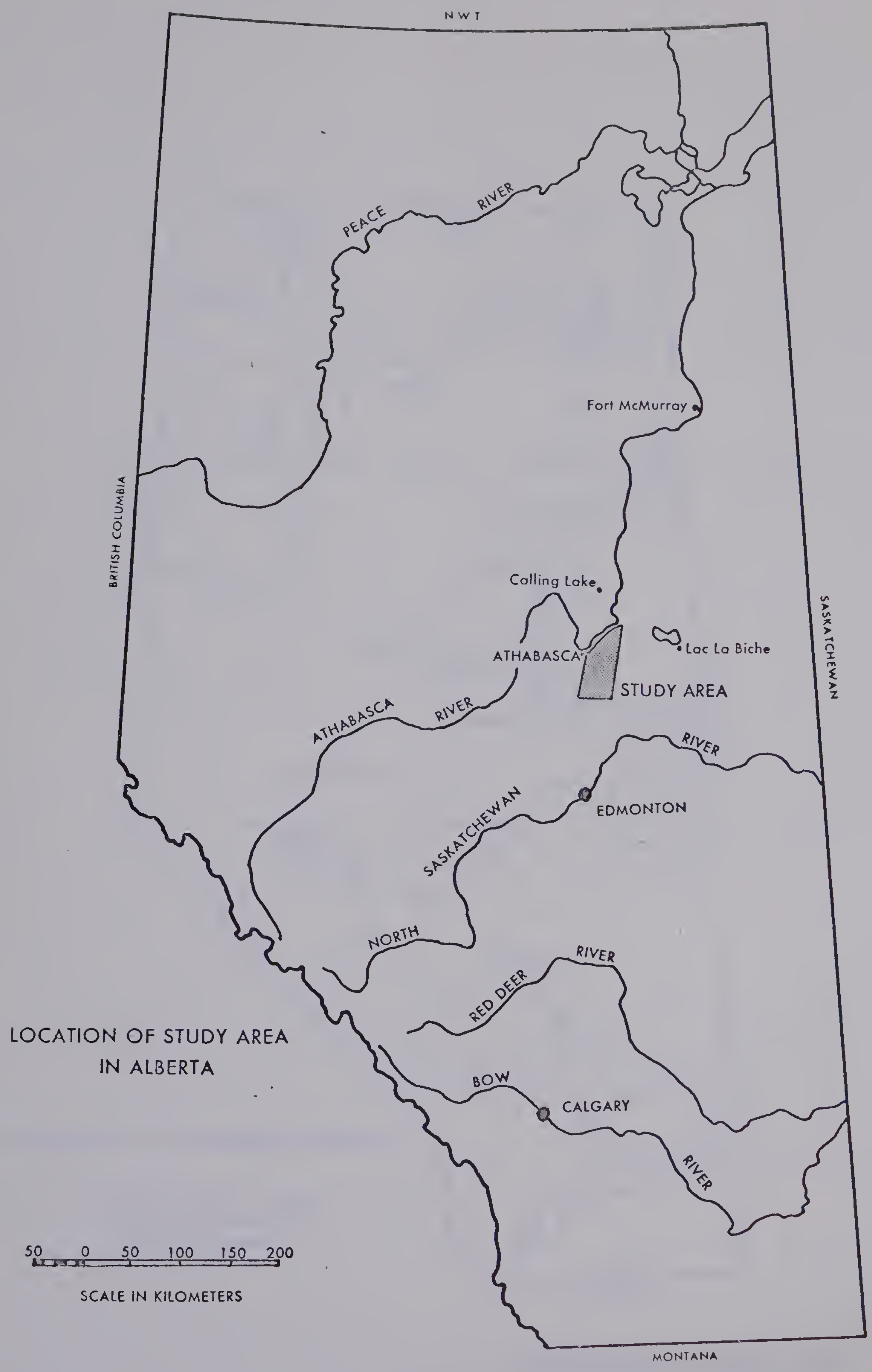
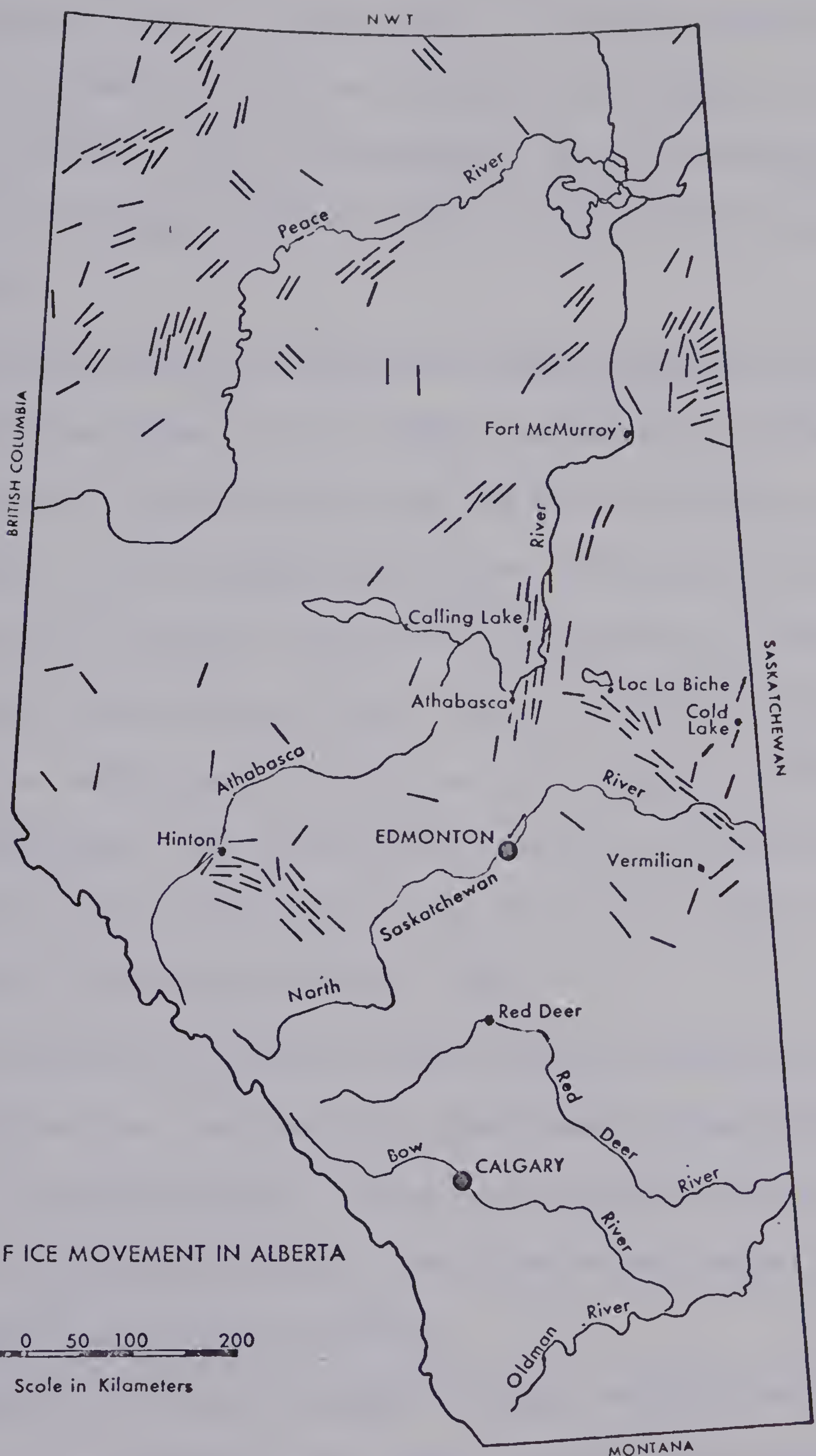

NWT
PEACE
RIVER
Fort McMurray
BRITISH COLUMBIA
Calling Lake
ATHABASCA
Lac La Biche
STUDY AREA
SASKATCHEWAN
ATHABASCA
RIVER
RIVER
SASKATCHEWAN
EDMONTON
NORTH
RIVER
RED DEER
LOCATION OF STUDY AREA
IN ALBERTA
BOW
CALGARY
RIVER
50 0 50 100 150 200
SCALE IN KILOMETERS
MONTANA

FIG. 2



DIRECTION OF ICE MOVEMENT IN ALBERTA

50 0 50 100 200
Scale in Kilometers

Source (Gravenor and Meneley, 1958)

FIG. 3

town of Athabasca.

Glacial History

A minimal amount of information exists on the Pleistocene history of the Athabasca area. The full effect of the first three stages of glaciation, Nebraskan, Kansan and Illinoian, on Alberta as a whole has yet to be resolved. Only the distribution of the Late Wisconsin ice is known with any certainty (Prest, 1970) and its limits at various times are debatable.

The Wisconsin stage of glaciation began approximately 80,000 to 100,000 years ago (Frye, et al., 1968). An initial ice advance covered most of Alberta. The source area for the ice is believed to be in the Keewatin area of the Northwest Territories. This advance was followed by a period of ice retreat that lasted approximately 20,000 years. The extent of this retreat is not known, but it is probable that the Athabasca area was deglaciated at this time, as evidenced at Watino (Pers. Comm., J. Westgate). The second major advance of the Late Wisconsin age occurred after this period and ice extended to the extreme southern limit of Alberta and into Montana (Prest, 1970).

Data concerning the glacial and post-glacial geomorphic history of the area, other than that concerning the origin of the flutings, was not gathered to any great extent. Field and laboratory analysis of the form of the flute crests and nature of the trough areas suggest that the following sequence of events took place.

A Keewatin ice lobe, or series of lobes, advanced over the Athabasca area during Late Wisconsin time. The position of the fluting ridges during formation relative to the position of the ice front is debatable, but several factors suggest that they were formed just prior to

total deglaciation of the Athabasca area.

It is likely that whatever mechanism operated during the formation of the flutings, it occurred in the final stages of glaciation. The possibility of having such features produced during an initial ice advance and maintained throughout glaciation is unlikely. Ice thicknesses of approximately 1,700 meters are assumed to have existed in the Edmonton area (Bayrock and Hughes, 1962), 130 kilometers to the south. The probability of having ice maintain a constant course, without even the slightest deviations, is minimal. Features such as flutings could not be maintained and most certainly would have been obliterated by the ice if any deviations from one constant course occurred.

Dilatant properties of till (Smalley and Unwin, 1968) must also be considered in this respect. Dilatant properties are those which allow the till to resist certain levels of applied stress beneath the glacial ice. Excessive shear stress levels, however, would be expected beneath a thick, moving glacier and would eliminate the flutings if they had been formed during an initial advance of the Late Wisconsin ice.

It is believed that following the formation of the flutes the final recession of ice was relatively rapid. A large majority of the till fabrics (See Chapter Three) taken from beneath the surface of the till plain yielded systematically significant orientation values. Ablation tills would not be expected to illustrate the systematically consistent preferred orientations as were found in the field area. Therefore, it is not believed that mass down-wasting of a debris-rich ice sheet occurred.

The field area is devoid of ice disintegration features. Air photograph examination revealed a relatively extensive field of prairie

mounds in an area twenty kilometers southwest of the fluting field, but nowhere did they actually encroach upon the flutings. The absence of ice disintegration features suggests that if ice did stagnate over the field area, it was free of englacial debris. A minimum date for deglaciation of the area is approximately 11,400 years ago (Lichti-Federovich, 1970).

Post-glacial History

The waning stages of the Late Wisconsin ice in Alberta saw the formation of numerous glacial lakes (Taylor, 1960). Some evidence has been gathered from a section of the fluting field that suggest that a portion of Lake Tyrrell, which covered a large area of northern Alberta, extended further south than originally suggested by Taylor (1960).

Taylor presented a map of the outline of Lake Tyrrell at its greatest extent and showed it to extend down a portion of the present day Athabasca River valley to approximately fifteen kilometers north of Athabasca. Field observations, discussed below, and data from surficial samples suggest that Lake Tyrrell extended further south.

In the course of field word it became evident that many of the larger flute crests deviated from the smooth, symmetrical cross-profiles generally observed. It was soon realized that the asymmetry was consistent and the following characteristics were observed. The largest flute crests were found to be asymmetric in an east-west direction, across the trend of the flutes, with the west side being the steepest. Higher concentrations of poorly stratified sand were found on the west sides of the flute crests dipping from 25° - 28° to the west. The crests were often flat-topped with concentrations of glacial erratics and sand on the crests. The sides of the ridges were occaisonally broken, or inter-

rupted, in a nearly horizontal, step-like fashion.

The above characteristics all suggest that the form of the ridges was modified by the existence of a lake which totally covered the flute crests. It is believed that as the lake level lowered the intensity of wave action on the crests increased, sorting the till and leaving only sand and large boulders on the crests. The bedded sand on the west sides is believed to have been deposited there from material originally found on the crests.

To test this hypothesis twenty samples were taken at ten centimeter intervals, beginning at a depth of 2.5 meters. If the above hypothesis is accepted, the samples should show an increase in mean particle size with decreasing depth. The lower-most layers, at 2.5 meters depth, are expected to have been deposited there when the lake depth was relatively great and the effect of wave sorting was slight. Qualitative field observations showed this generally to be true.

The sand samples were sieved as indicated in the flow chart (Fig. 4). Table 1 shows the results obtained from the sieving with the four statistical parameters (Folk and Ward, 1957), each of which can be obtained by the following equations:

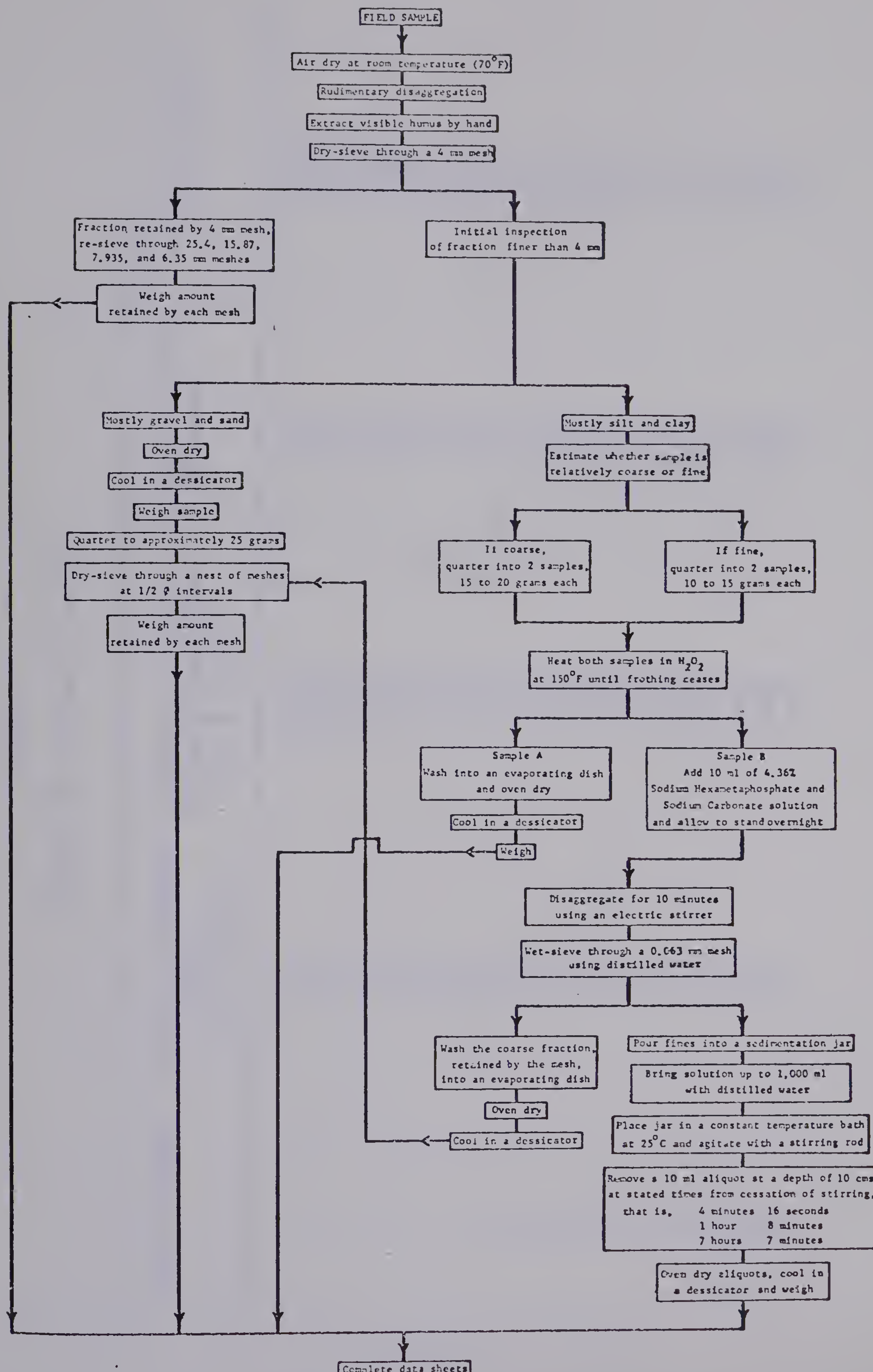
Graphic Mean (in ϕ units) $\frac{\phi16+\phi50+\phi84}{3}$

Graphic Standard Deviation (in ϕ units) $\frac{\phi84-\phi16}{4} + \frac{\phi95-\phi5}{6.6}$

Graphic Skewness $\frac{\phi16+\phi84-2(\phi50)}{2(\phi84-\phi16)} + \frac{\phi5+\phi95-2(\phi50)}{\phi95-\phi5}$

Graphic Kurtosis $\frac{\phi95-\phi5}{2.4(\phi75-\phi25)}$

Fig. 5 shows the resultant graphs when the parameters of graphic mean grain size and graphic standard deviation are plotted against decreasing depth. With respect to grain size, there is no apparent trend, except for samples 11-15 where a consistent increase in the mean parti-



Flow Chart for Mechanical Analysis of Samples
FIG. 4

TABLE 1

RESULTS OF SIEVING OF SANDS

Sample Number	Inclusive Graphic Mean (In Ø units)	Inclusive Graphic Standard Deviation (In Ø units)	Inclusive Graphic Skewness	Inclusive Graphic Kurtosis
1	1.90	1.035	.268	1.285
2	1.96	1.025	.270	1.250
3	1.90	1.192	.253	1.410
4	2.04	.827	.261	1.443
5	2.30	.990	.255	1.180
6	2.88	.674	.146	1.161
7	1.99	.821	.074	1.048
8	2.28	.854	.046	1.131
9	1.99	.650	.019	1.064
10	2.00	.741	.110	1.129
11	1.80	.667	.053	1.115
12	1.74	.723	.141	1.348
13	1.66	.784	.187	1.557
14	1.29	.843	.297	1.523
15	.93	1.256	.453	1.226
16	1.93	1.097	.051	1.241
17	1.46	.872	.014	1.410
18	1.45	.747	.217	1.709
19	1.67	.543	.039	1.059
20	1.92	.531	.039	1.056

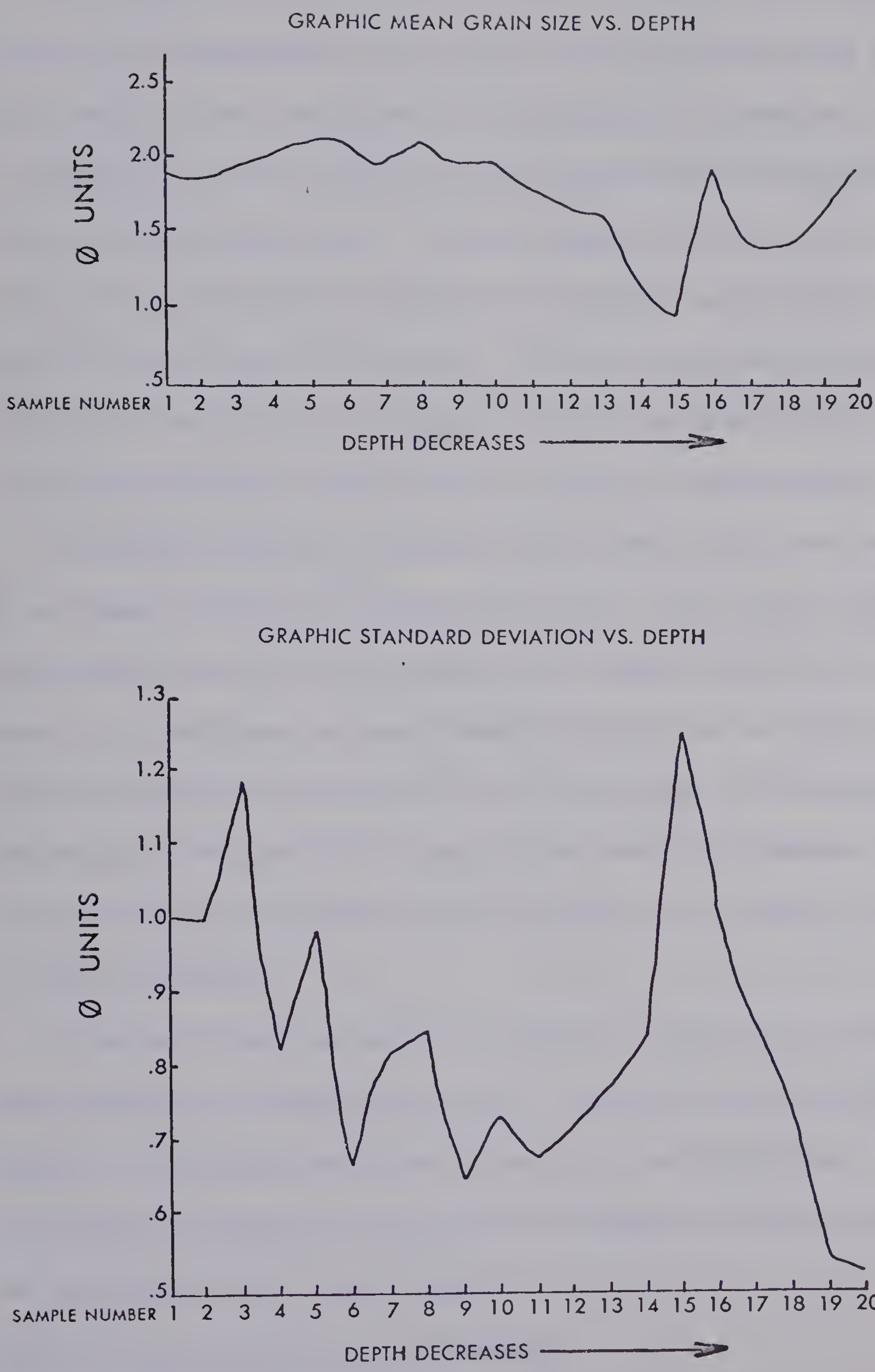

GRAPHIC MEAN GRAIN SIZE VS. DEPTH
Ø UNITS
2.5
2.0
1.5
1.0
.5
SAMPLE NUMBER 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
DEPTH DECREASES
GRAPHIC STANDARD DEVIATION VS. DEPTH
Ø UNITS
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
SAMPLE NUMBER 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
DEPTH DECREASES

FIG. 5

cle size is observed. Standard deviations, a measure of the degree of sorting, for the same group of samples show a similar increase in value of (Ø) unit, indicating poorer sorting with each sample.

The variations of intensity of wave action cannot adequately be defined or interpreted, as the results were obtained from only one site. Daily and seasonal variations can be expected to mask the effects of any sequence of lake levels and may tentatively be considered as responsible for deviations from a uniform sequence of lake-level lowering. Ice to the north might be expected to retreat erratically, allowing new outlets for the lake to develop. The lake level would be expected to vary as new outlets were formed. No definite trends, therefore, can be defined with respect to the rate at which the lake lowered.

Following complete drainage of the lake in the area the Athabasca River began to flow through the field area. Its course had deviated southwards from the Calling Lake area, eighty kilometers to the north where it is believed to have flowed into the Lac La Biche area (Fig.2). The Tawatinaw River enters the field area from the south and enters the Athabasca River immediately east of the town of Athabasca. The Tawatinaw River was a spillway for a pro-glacial lake which existed south of the field area.

Numerous slump features are visible on the valley sides of both the Athabasca and Tawatinaw Rivers. A minor field of sand dunes is found in the extreme northeast section of the field area. The dunes are parabolic-shaped and the sand is presumed to have originated from the re-worked till of the ridges.

Distribution and Form of the Flutings

The field of flutings is divided into two main sections, one loca-

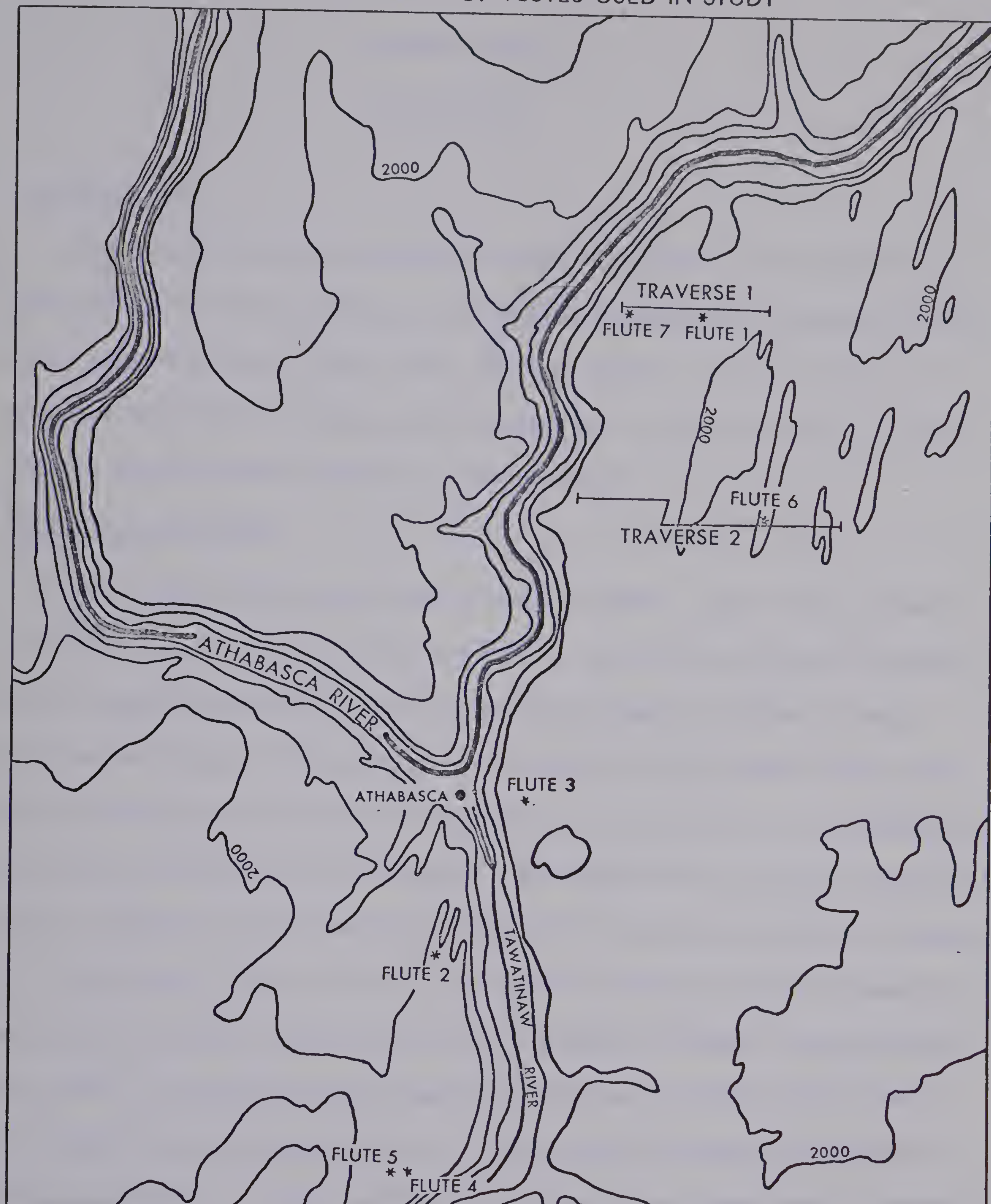
ted east and northeast of the town of Athabasca and the other to the south (Fig. 6). The general trend of the flutes is from 15°. The ridges in the north are generally much larger, both in over-all length and height. An exception occurs in the extreme southern limit of the field, where two ridges, more closely resembling drumlins in form, were measured to be over twenty meters higher than the adjacent troughs.

The ridges tend to exhibit a blunt nose appearance only in those that are larger than two to three meters in height. The smaller ridges rise imperceptibly out of the till plain without exhibiting a blunt nose form. It was often difficult to interpret precisely the exact limits of the small ridges because of this gradual rise.

The flutings are symmetrical in cross-profile on both large and small scale features. Exceptions to this form are believed to be due to the modifying effect of the wave action of the pro-glacial lake. The longitudinal profiles are very smooth and uniform heights are maintained for several kilometers along the crests. The presence of vegetation on many of the flutes made exact measuring of the total lengths impossible. Many of the larger flutes were measured on air photographs and found to be over ten kilometers long.

The northeast sector of the field has the most dense concentration of ridges and troughs. The nature of the topography and vegetation, however, made it impossible to examine these flutes other than on air photographs. The ridges are densely wooded, with the intervening troughs often being filled with small, elongated lakes or marsh land. As farming is impractical no roads crossed this area and access was impossible.

LOCATION OF FLUTES USED IN STUDY



FLUTES * TRAVERSES CONTOURS 2000

CONTOUR INTERVAL 100 FEET

5 0 5 10

SCALE IN KILOMETERS

FIG. 6

CHAPTER THREE

METHODOLOGY

Introduction

The procedures to be followed in the Athabasca fluting field were designed to discover pertinent information concerning the physical structure, composition and form of the fluting ridges. The data collection was directed toward testing a given hypothesis, and the form of the data related to the chosen analytical manipulation.

Till Fabric Analysis

Till fabrics have been used by Holmes (1941), Hoppe (1951), Harrison (1957), Harris (1969), Boulton (1970) and numerous others to determine, among other things, the line of ice movement in areas of basal till accumulation. The deposition of basal till (Harrison, 1957; Boulton, 1970) involves the slow accumulation of material as it is gradually released from the base of a glacier. This mass has a very high ratio of debris relative to ice (Boulton, 1968) and is termed the glacier "tectonite" (Harrison, 1957, p. 291). This mass is thought to have gradually accumulated beneath the moving ice by a process of basal freezing (Boulton, 1970). Eventually the "plasticity" of the ice (See Chapter Four) is reduced and the basal till is no longer able to move with the overlying clean ice. A shear surface at the top of the debris-rich mass may be formed and the overlying ice moves over the till (Boulton, 1970).

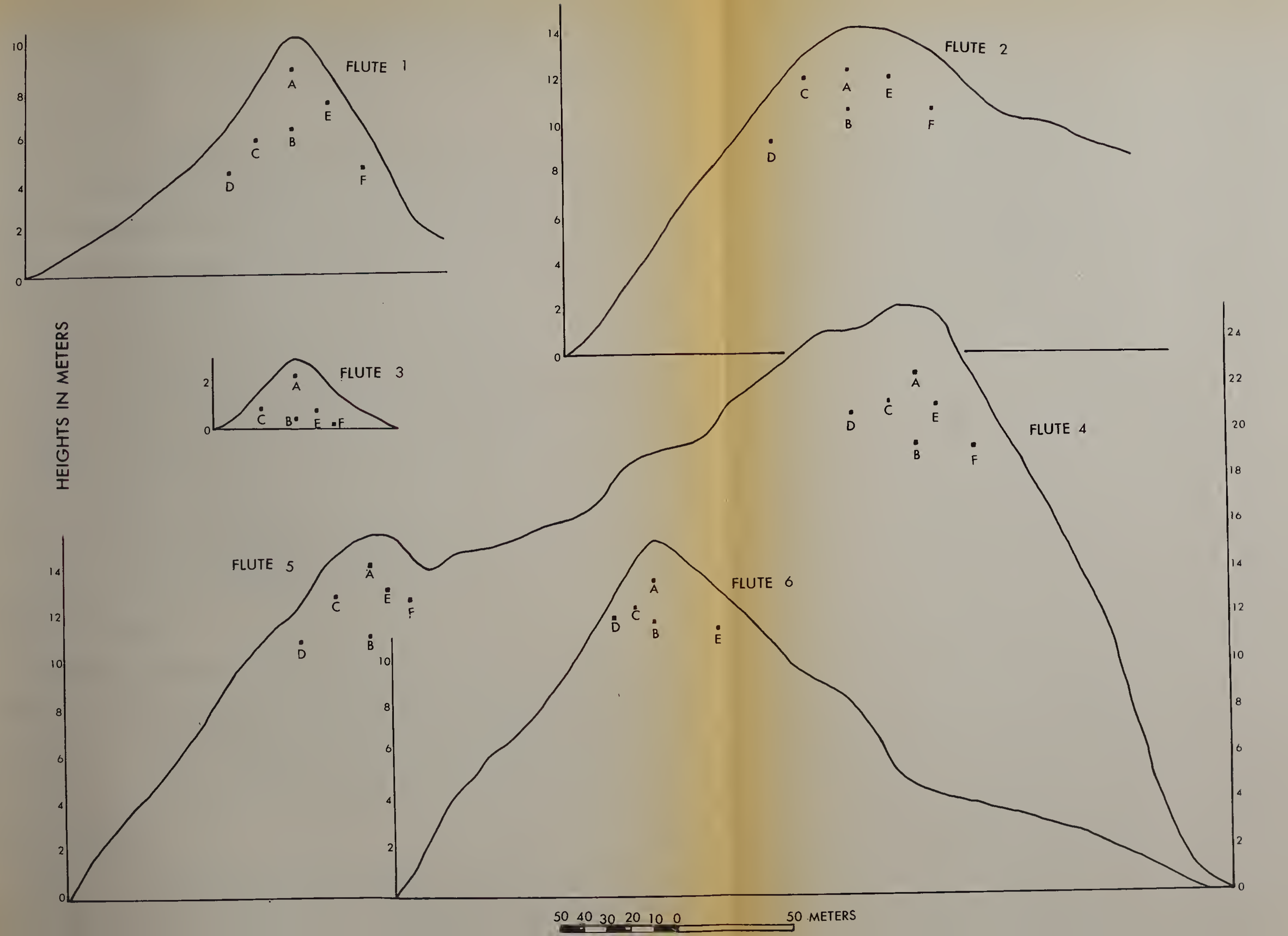
The orientation of particles within the till mass is thought to occur in the transportational environment (Harrison, 1957) and not in the actual deposition process (Holmes, 1941). Two modal fabric orienta-

tions commonly are found in the till fabric. One mode parallels the line of ice movement and a second mode is transverse to that direction. The pebble orientations represent a stable form of positioning of particles with respect to the line of ice movement.

Theoretically only in a deposit of basal till will this parallel fabric with the transverse fabric be visible. The deposition of ablation till is not as orderly a process as basal till deposition and regionally inconsistent fabrics should be found. Some orientation of pebbles may occur due to sliding of ablation till off or down an ice surface, but a consistent regional fabric would not be expected.

In the Athabasca area till fabrics were taken from seven roadcuts distributed throughout the fluting field (Fig. 6). The distribution of fabric sites adequately covers the entire field. The pattern of sampling at each roadcut was predetermined to allow optimum coverage at each crest and still allow for full coverage of the entire field. The sampling layout at each site can be appreciated from Fig. 7. It can be seen that two fabrics were taken from the center of the roadcut and up to two fabrics were taken at either side of the crest. As the size of the fluting ridges and depth of the roadcuts varied, no specific distances east or west of the center could be chosen for these fabric sites. A ratio of one third and two thirds of the way outwards from the crest was thus chosen. By employing this kind of ratio relative distances from the crests could be approximated regardless of flute size.

Six fabrics were taken at four of the roadcuts. At flutes 3 and 6 only five fabrics were taken (Fig. 6) as the presence of vegetation or depth of the roadcut made a sixth site inaccessible. Owing to time and weather restrictions only one fabric was taken at flute 7.



HEIGHTS IN METERS
FLUTE 1
FLUTE 2
FLUTE 3
FLUTE 4
FLUTE 5
FLUTE 6
50 40 30 20 10 0
50 METERS

At each fabric site a one square meter area was cleaned off and at a distance of approximately one half meter in from the face of the road-cut the long axis trends and plunges of fifty pebbles were noted. Pebble orientations were noted to an accuracy of plus or minus 5°. Orientations were made with a Brunton compass adjusted for a magnetic declination of approximately 23°E.

Pebbles were found on a vertical face by scraping at the till matrix until a pebble was encountered. The matrix surrounding the pebble was carefully removed so as not to disturb the orientation of the pebble. It was then examined in situ to determine if the axial ratio (a:b) was sufficiently large to declare one axis the definite "a". Minimum ratios of 3:2 were chosen and observed as the lowest limit for acceptance. If the axis of the pebble did not exhibit this minimum ratio it was removed and discarded. The orientation of those pebbles that were accepted was measured with the Brunton compass and the azimuth was noted. The angle of plunge of each pebble was measured by using the level on the compass and visually extending the long axis. By noting the trend and plunge of the "a" axis each pebble's position in space is specified.

Microfabric Analysis

Microfabrics were also taken from each fabric site. The fabric orientations of the sand and silt sized particles essentially illustrates the same pattern as the macrofabric (Ostry and Deane, 1963; Sitler, 1968). Therefore, the microfabrics could act as a check on the macrofabric orientations.

A block of till measuring approximately 5cm. x 5cm. x 5cm. was cut from the till face. To facilitate ease in handling a cube was carved by planing off the sides with a knife. The top surface was smoothed,

leveled and a north orientation was carved to fix the in situ orientation. The blocks were carefully removed and placed in plastic bags. The samples were later air dried and subsequently impregnated in a resin. Two thin sections were cut from each block corresponding to the horizontal plane and a vertical plane parallel to north. The thin sections were placed in glass slides and the orientations of the sand and silt grains were then noted through a microscope.

Certain discrepancies can occur in the microfabric and macrofabric orientations that may be attributed to the depositional process, subsequent settling of the till or the actual preparation process of the slide. Disc and blade shaped particles tend to illustrate a transverse orientation (Holmes, 1941). The smaller particles must be considered more susceptible to disturbance by frost action and settling and their orientations are somewhat less pronounced (Harris, 1969). During the cutting process a certain number of "accidental" long axes may be created when the thin section is being made. All these factors may distort to some degree the original fabric orientation.

Presentation of the Fabric Data

All the macrofabrics were plotted in two ways, on rose diagrams and on contoured stereographic diagrams. Rose diagrams are frequency-distribution diagrams and are plotted by counting the number of observations in each 10° sector from 1° to 180° and the corresponding 10° sectors from 181° to 360°. Thus they represent mirror image diagrams of the two-dimensional long axis trends of the pebbles.

The stereographic diagrams were plotted by computer (Cruden, 1966). They are useful for the presentation of fabric data because they combine both the trend and the plunge of each pebble observation on one dia-

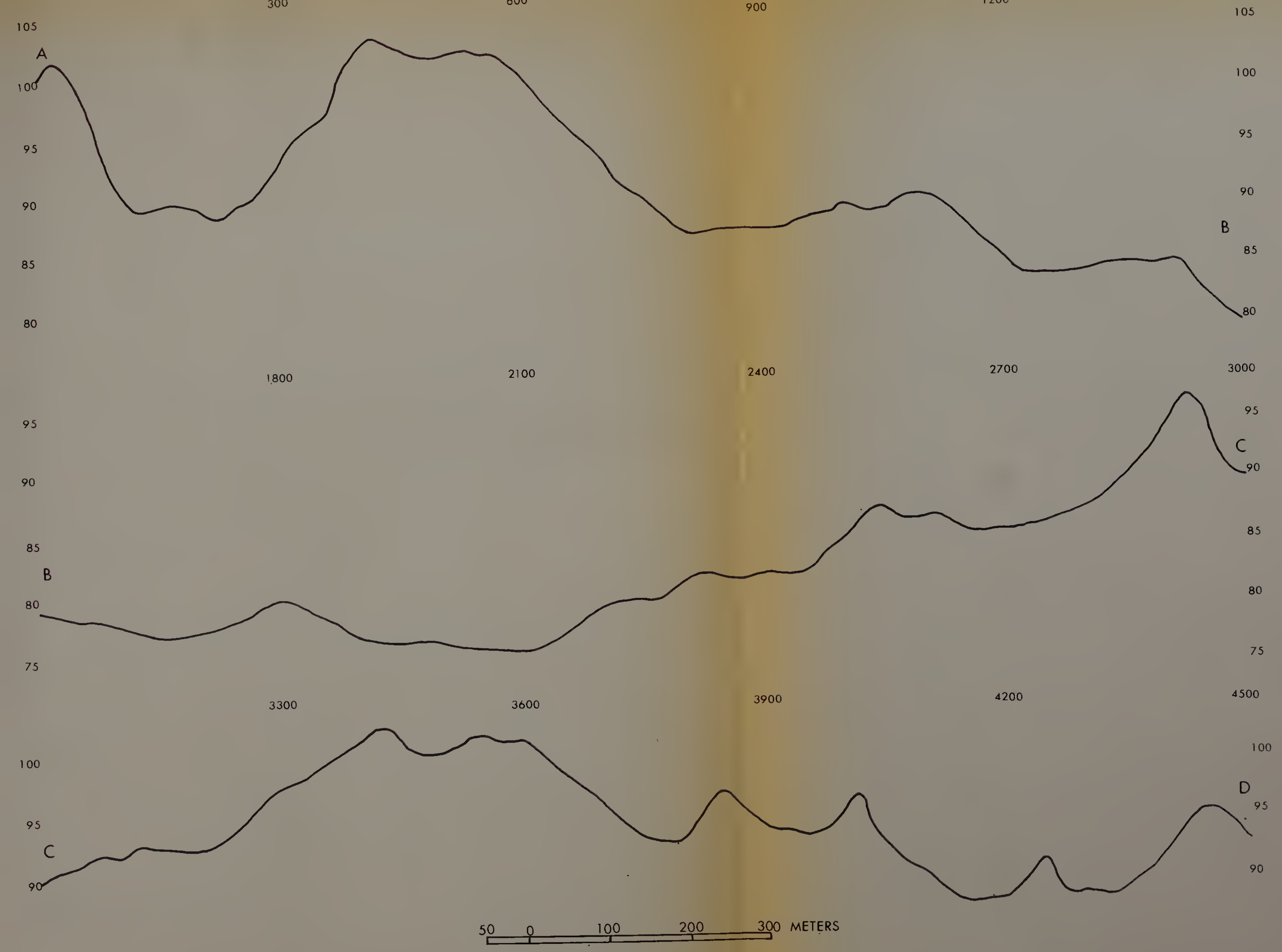
gram (See, for example, Johansson, 1963). They are plotted on a circular diagram. The perimeter of the circle represents 0° plunge and plunge values gradually increase to 90° at the center of the circle. Degrees of azimuth are found on circumference of the circle.

The combination of trend and plunge of each pebble observation for each fabric site would result in fifty points on each diagram. A small circle that represents some percentage of the total area of the diagram is drawn around each point. The number of observations lying within each small circle is noted and expressed as a percentage of the total number of points within the diagram. Because this procedure was performed by a computer even numbers appear on each diagram. Contours are drawn around the numbers. A two per cent interval of contour lines was chosen for each diagram. The rose and contour diagrams for the thirty five macrofabric sites are presented in the Appendix.

Profile Mapping

Mapping along transects which cut across a series of flute crests and troughs was undertaken following the work on the till fabrics. Two transects, one of 4,500 meters length and another of 7,500 meters, were mapped. The first transect was mapped using a microscopic alidade and plane table and the second was mapped using a theodolite. Use of the alidade and plane table proved to be too time consuming, as it involved numerous leveling processes of the table and the instrument and a limited viewing distance. The theodolite was used during the second transect and proved to be much more efficient. Leveling procedures were reduced and longer sightings could be made across wide, level areas. The two profiles are illustrated in Figs. 8 and 9.

The profiles were measured in order to obtain detailed information



VERTICAL EXAGGERATION X 15

TOTAL LENGTH OF TRAVERSE 4500 METERS

CROSS-FLUTE PROFILE TRAVERSE 2

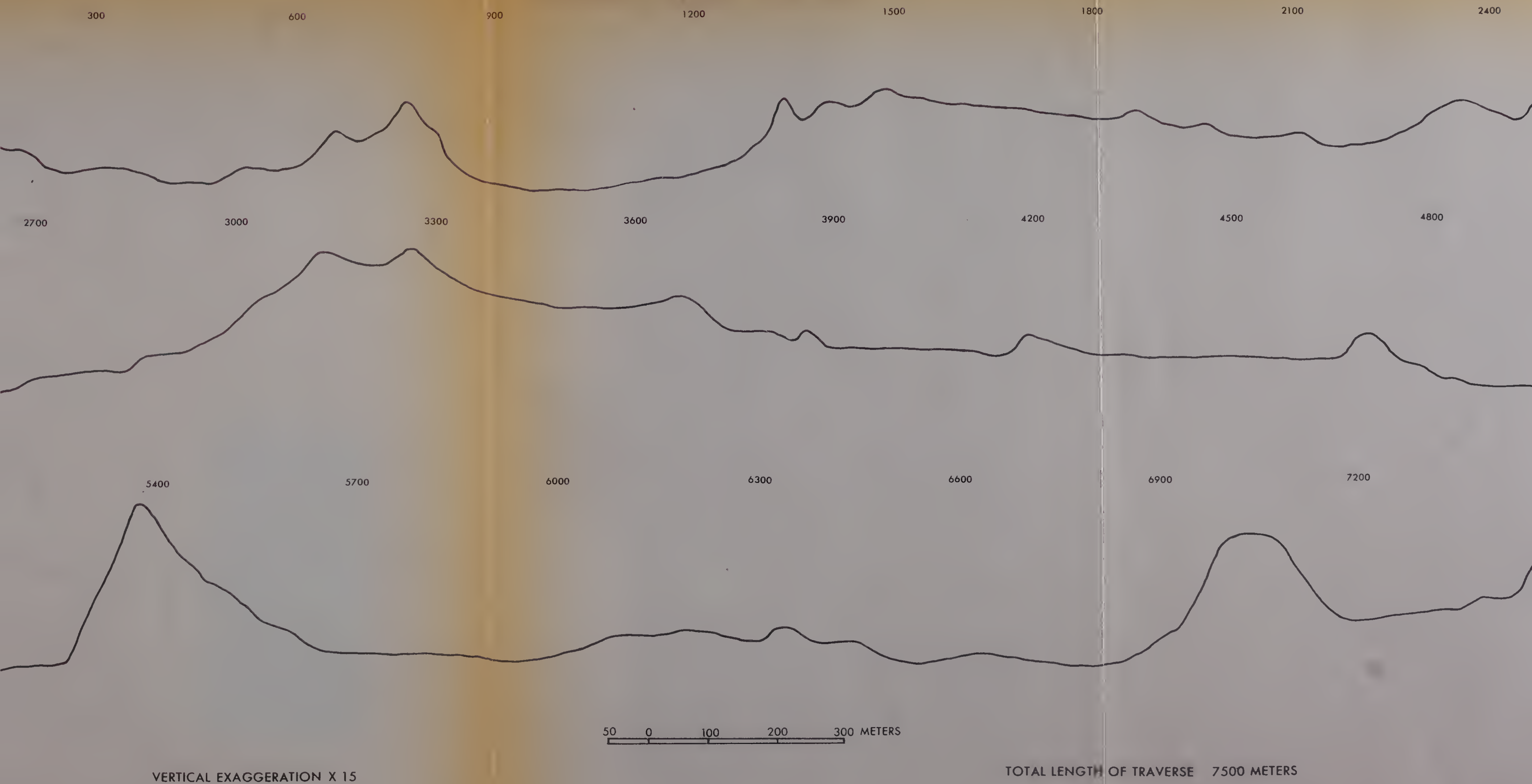


FIG. 9

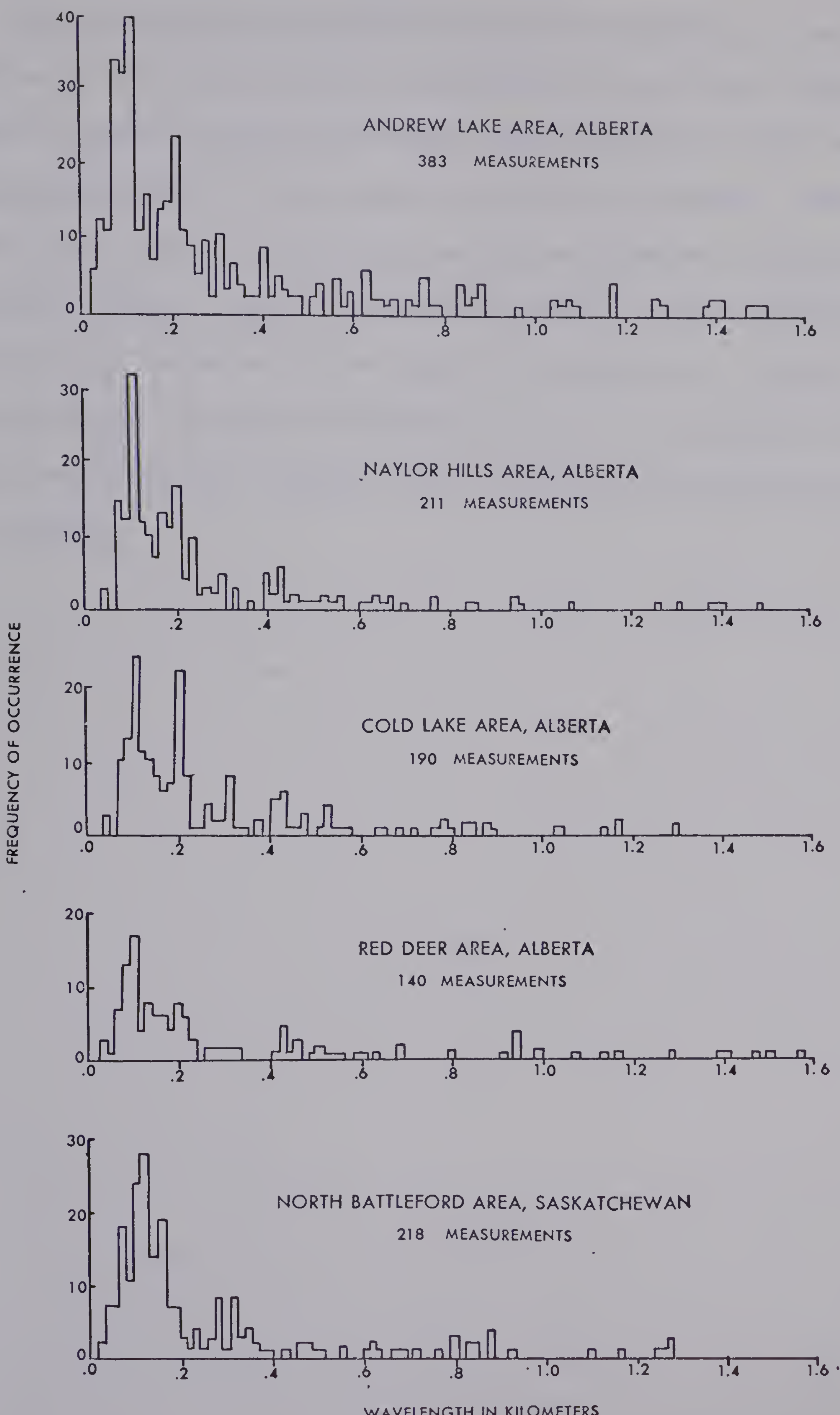
concerning the form and spacing of the fluting ridges and troughs. Gravenor and Meneley (1958) and Reed, Galvin and Miller (1962) presented information on relatively consistent spacings of flutings and drumlins respectively. Gravenor and Meneley (1958) examined air photographs and measured the distances between adjacent crests and presented frequency diagrams of the spacings, or wavelengths, of the flutings. They found a preferred spacing across the fluting fields with a modal value of between 90 to 120 meters. A secondary peaking of approximately 200 meters in nearly all fields examined was also found to exist (Fig. 10).

It is believed that the preferred spacings quoted by Gravenor and Meneley may be invalid. Only those flutings that were sufficiently large to be seen on high altitude air photographs could have been included in their data. During field reconnaissance it became evident that features obvious in the field often were not visible on the high altitude air photographs. In one location east of Athabasca only two flutings were visible on the air photograph while seven were seen in a ploughed field. Five flutings, therefore, would not have been included in any air photographic analysis of even this small area. The discrepancy will be greatly compounded when areas of dense vegetation cover are examined. Smaller flutings and even some of the larger ones, perhaps up to two meters height, could not be identified on any high altitude air photographs. Therefore, the use of air photographs by Gravenor and Meneley would make their data invalid.

Sediment Collection

At each till fabric site sediment was gathered for mechanical analysis. Several hundred grams of till were brought back to the laboratory and prepared as outlined in Fig. 4. Sieving and pipette methods were

FLUTING WAVELENGTH DISTRIBUTION



DATA FROM (GRAVENOR AND MENELEY, 1958)

FIG. 10

used in the analysis of the samples.

The till samples were gathered in order to determine if any consistencies or variations may have existed either across flute crests or along the entire length of the field. Hoppe and Schytt (1953) found sand concentrations on the crests of small scale flutings. Such variations could have had some bearing on the localization of flutes in the Athabasca region. Gravenor and Meneley (1958) and Aranow (1959) found that textural variation did not exist in the flutings or drumlins that they examined. The fact that flutings can occur in crystalline bedrock and in drift deposits indicates that textural variation does not localize flutings.

CHAPTER FOUR

MOVEMENT AND INTERNAL MOTIONS OF ICE AND WATER

Introduction

The movement of a glacier is not fully understood. Present day glaciers are found in relatively inaccessible areas and studies of their internal structure face considerable difficulties. Consequently much work on glacier movement is highly theoretical and is commonly based on laboratory experiment. While numerous data exist on surficial ice velocities (Paterson, 1969) very little is known about basal ice velocities of temperate glaciers, where up to ninety per cent of glacier movement may originate (Pers. Comm., W. Harrison).

The movement and internal motions of water, while more complex, are easier to study and have received more attention than has the problem of ice flow. Many fluvial processes and the motions involved may be duplicated with relative ease in the laboratory and eddies and related flow patterns can be observed and regulated under controlled conditions (Allen, 1969). Such experiments are difficult to perform with ice because the movement is exceedingly slow (Kamb, 1964).

Movement of Glacial Ice

There are two main ways in which a glacier may move, by ice deformation and by basal sliding. Ice deforms in a "plastic" manner when crystals of ice glide over one another in layers parallel to the basal plane of the ice crystals. Basal sliding involves two processes, pressure-melting and enhanced plastic flow. Each of these two methods will be considered.

<u>Ice Deformation</u>

The movement of glaciers by ice deformation has been examined by Nye (1951), Glen (1958), Paterson (1969) and others. It involves the movement, or gliding, of layers of polycrystalline ice parallel to a basal plane. The force that initiates movement is termed shear stress (τ) and the rate of deformation is termed the strain rate (ξ).

The formulation of a flow law was undertaken by Nye (1951) and resulted in the equation

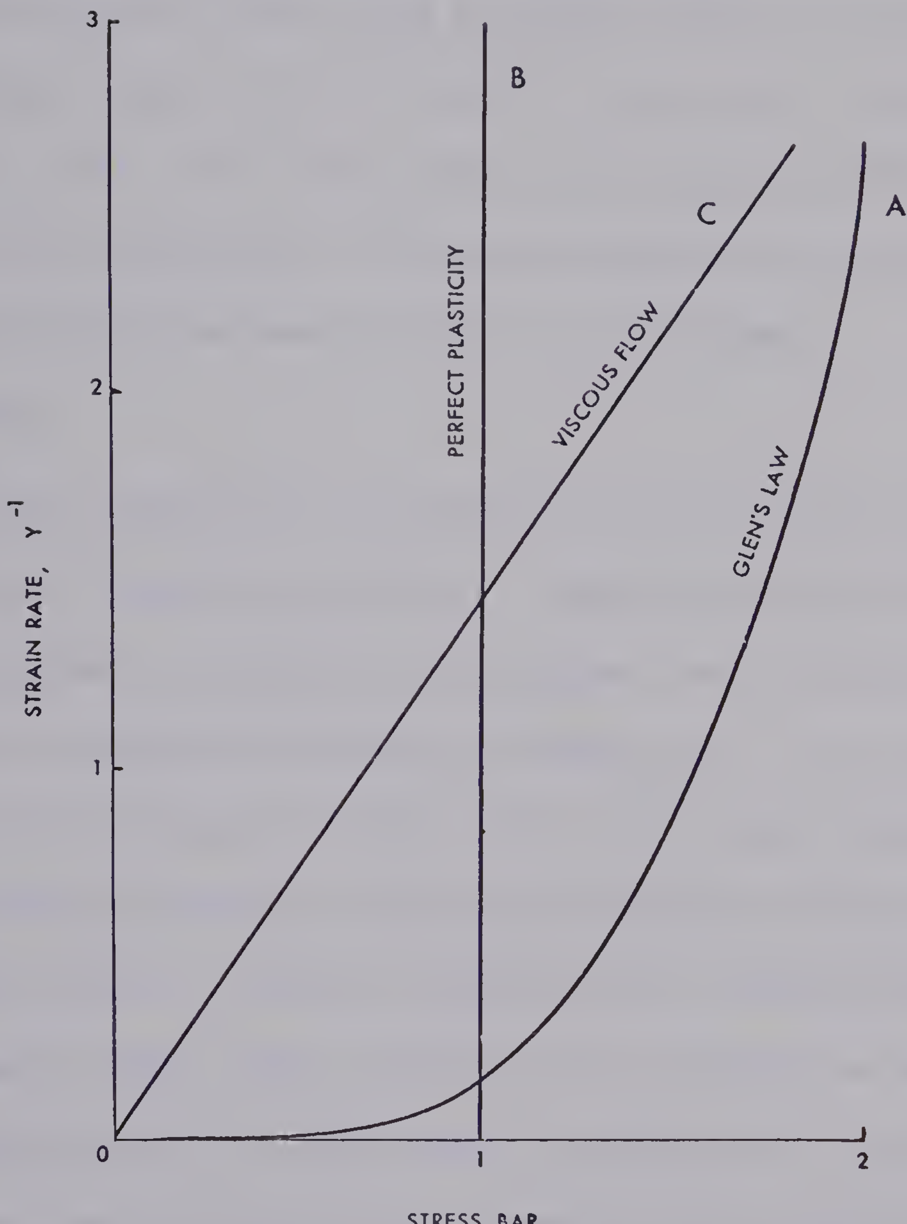
$$\xi = A\tau^n$$

where ξ is the effective strain rate, τ is the shear stress and A and n are empirical constants. "A" is dependent on temperature and may be assumed to represent the viscosity of ice. "n" is not temperature-dependent and has a range of from 1.9 to 4.5, with a mean value of approximately 3. In essence the formula states that the strain rate in years^{-1} is proportional to the shear stress in bars (1.02 Kg./cm^2 = 1 bar).

With the application of an initial shear stress the strain rate will increase until a constant level, or rate, of deformation is reached. The initial deformation rate is transient and is generally assumed to be negligible when considering total ice movement. When the rate of deformation becomes constant, "creep" is said to exist. When higher levels of stress are applied an increase in the strain rate may occur. The increase is assumed to result from the gliding of more favorably oriented polycrystals.

Fig. 11 (After Paterson, 1969) illustrates some fundamental concepts related to ice flow. Curve "C" represents viscous flow and shows that stress is linearly related to the rate of strain. Curve "B" shows that with a shear stress less than one bar no strain is produced. At

RELATION BETWEEN STRAIN RATE AND STRESS



FROM (PATERSON, 1969)

FIG. 11

one bar, however, the strain rate becomes very large. A substance reacting to stress in such a manner is said to be "perfectly plastic" with a yield stress of one bar. Ice, however, has never been shown to have a yield stress; the lowest applied stresses have always produced some deformation (Paterson, 1969).

Glen's flow law, curve "A", shows that there is essentially no appreciable deformation when shear stresses are less than .5 bars. This helps to distinguish viscous flow from Glen's flow law for ice. "A" and "C" approximate each other, but differ in the respect that relatively large strain rates result from small shear stresses in "C" but not in "A". "A" is an exponential funtion and exceeds the strain rate of "C" when a stress of approximately three bars is reached.

Basal Sliding

The second component of ice movement, that of basal sliding, is expected only in temperate glaciers. Temperate glaciers are those that are at the pressure-melting point throughout that part of the glacier not exposed to seasonal variations in temperature. If a glacier is frozen to its bed (Goldthwait, 1960) it does not slide. Weertman (1957; 1964) and Kamb and LaChapelle (1964) have suggested theories on how basal sliding takes place. Lliboutry (1968) has also examined basal sliding.

Weertman's (1957; 1964) theories first consider the aspect of pressure-melting of basal ice layers when in contact with the upstream side of obstacles. As ice approaches an immovable obstacle excess pressure is exerted on the upstream side, depressing the melting point, causing the ice to melt. The meltwater is transferred to the downstream side of the obstacle, where, due to tensile stress acting away from the obstacle, the pressure is less and the meltwater can refreeze here. The

process of refreezing on the downstream side is termed regelation. The regelation process causes a glacier to "melt" through obstacles implanted in the basal material. Latent heat is given up in the freezing process and transferred back through the obstacle and aids in the melting process of the upstream side. The maximum obstacle size for this process to be effective is approximately one meter long. For sizes larger than this the effect of transferring latent heat is minimal because the larger volume would cause the heat to be too dispersed and it could not aid in the melting process.

The second process in the theory of basal sliding is that of enhanced plastic flow. This is assumed to have an effect because all the ice in the temperate zone is deforming plastically. The longitudinal stress will increase when ice encounters large obstacles and when the stress increases, the strain rate will also increase (Fig. 11). Since velocity is proportional to strain rate times distance, larger obstacles will allow for greater distances over which the stress may be enhanced. The velocity, therefore, will also increase.

The above theory of Weertman (1957) assumes only one obstacle size is involved, which is unrealistic. Later he modified the theory (Weertman, 1964) to account for varying obstacle sizes and introduced the effect of a thin layer of water at the base of ice on the rate of sliding. Obstacles smaller than the "controlling obstacle size" would be submerged beneath the layer of water. The larger obstacles, therefore, would be forced to support stresses greater than normal, thus increasing the rate of plastic flow and the sliding velocity. Weertman (1964) calculated that a water layer one tenth the controlling size might increase the sliding velocity by twenty per cent.

Flow within Fluid Mediums

Internal motions involved in the movement of fluid mediums can vary from simple laminar flow to complex forms of turbulent flow. Laminar flow is characterized by layers of fluid moving parallel without intermixing and may result in exceedingly slow-moving fluids. Turbulent flow generally accounts for the rest of fluid flow in air and water and is characterized by the formation of numerous eddies within the medium.

It is possible to distinguish between laminar and turbulent flow by use of the Reynolds number (R), defined by the equation

$$R=\frac{U\cdot D}{V}$$

where (U) is the velocity of flow, (D) is the depth of the flow system and (V) is the kinematic viscosity. The boundary between laminar and turbulent flow occurs at a value of approximately 300.

There is a special type of flow, however, that occurs under both laminar and turbulent conditions which is not characterized by the random formation of eddies, as in turbulent flow. Rather it is characterized by the orderly formation of corkscrew vortices oriented parallel to flow (Taylor, 1923; Allen, 1969). The vortices are found to exist contemporaneously with the flow characteristics under which current ripples are formed (Allen, 1969).

Secondary Flow in Water

Allen (1969), working with a flume tank, examined the types of bed forms produced under varying flow regimes. He found that in addition to normal current ripples oriented perpendicular to flow, termed "streamwise" ripples, a series of longitudinal ripples, termed "spanwise" ripples, were also produced. Allen found that there was a relationship between the bed forms produced and the dynamics of the fluid flow. The

flow patterns, discussed below, were responsible for propagating the features in an apparent systematic manner.

Geometry of the Bed

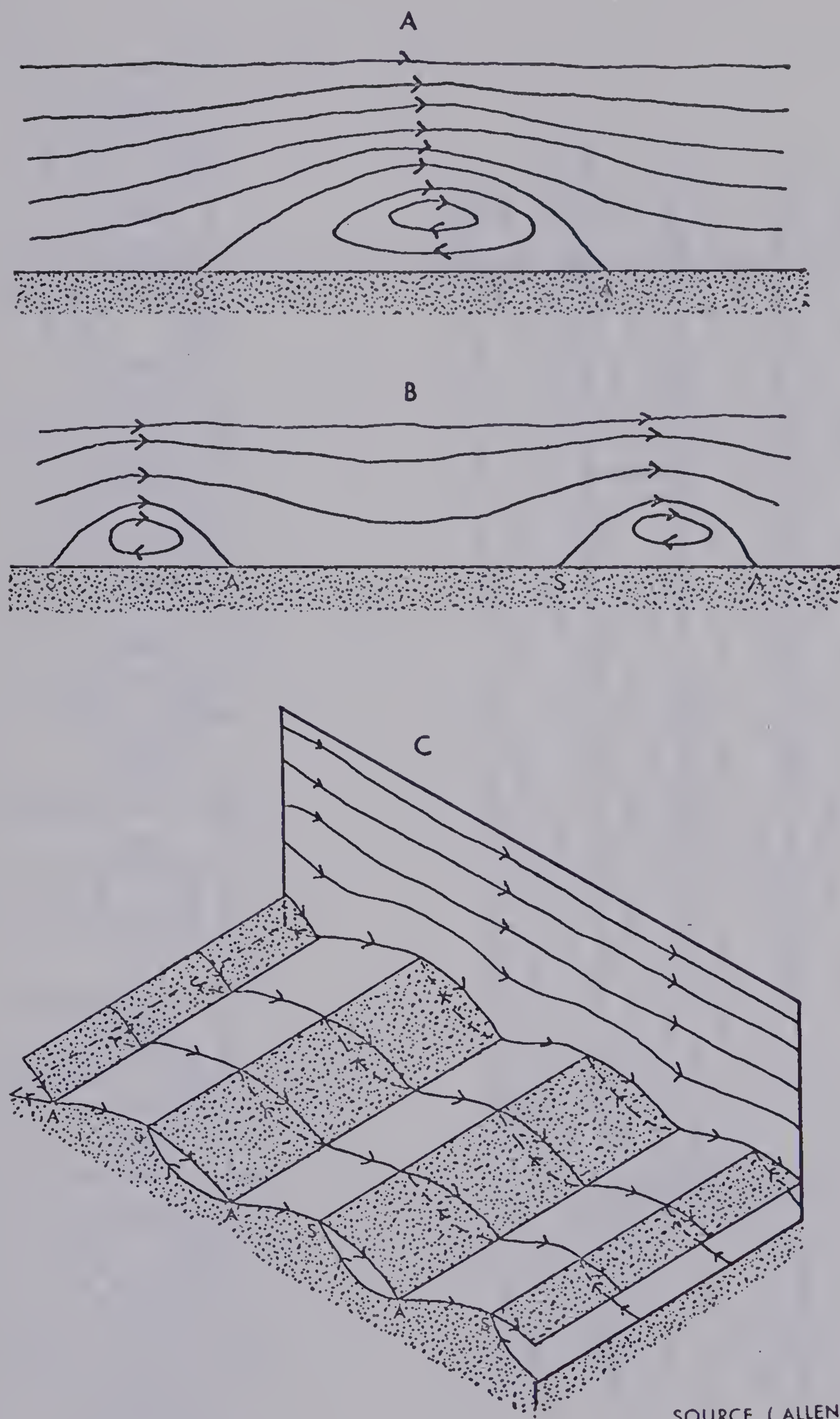
The bed forms produced were on a loose grain surface. Allen found that the geometry of the bed was the result of the evolved flow over the bed. As a fluid moved over the bed, regions of instability were created whereby the flow lines adjacent to the bed, termed "streamlines", separated from the bed (Fig. 12-A). Downstream from this zone the streamlines returned to the bed and attached to it. These points are respectively referred to as "separation" and "attachment" points. The flow lines within S-A (Fig. 12-A) are closed cells oriented perpendicular to flow and are termed "separation bubbles."

If this pattern is extended to include several equally spaced regions of separation and attachment it would have the appearance of that in Fig. 12-B. Once grain entrainment takes place the bed form will begin to resemble that in Fig. 12-C. It can be seen that a separation bubble is held captive to the lee of the ripples and the corresponding attachment point exists immediately in front of the next ripple (Allen, 1969). The resulting geometry of the bed is, therefore, a result of the evolved flow.

Spanwise Instability

Briefly, the above theory can account for the occurrence of streamwise ripples. If, however, a spanwise bed form is to be produced contemporaneously with these features, there is only one form that the flow can take: that form is one of spiral vortices oriented parallel to flow (Allen, 1969). A series of these vortices would appear as in Fig. 13. It can be seen that the streamlines have an opposite sense of

FLOW FIELD OF A RIPPLED BED



SOURCE (ALLEN, 1969)

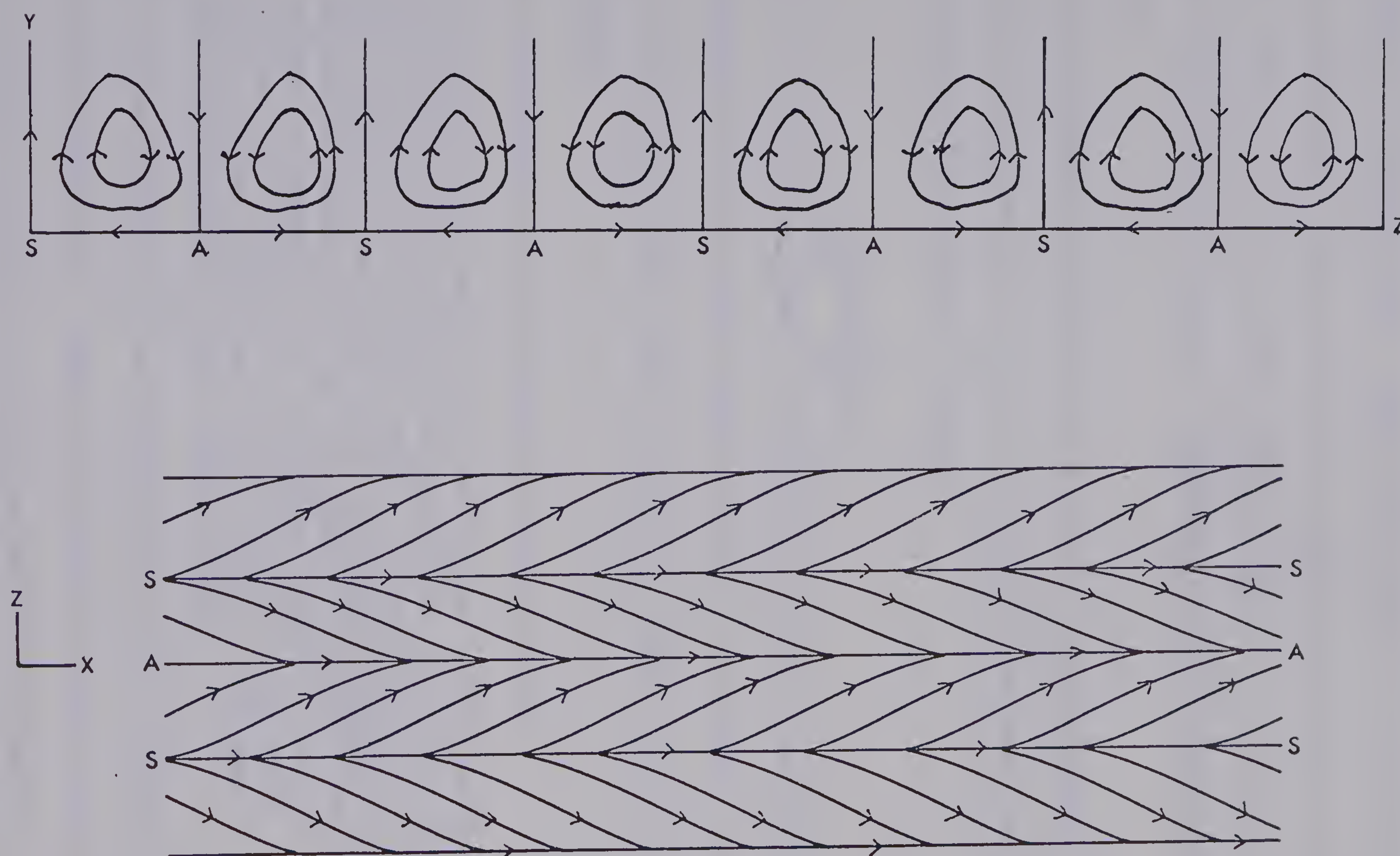
STREAMLINES ⟶

ATTACHMENT POINT A

SEPARATION POINT S

FIG. 12

PATTERNS OF FLOW DUE TO TRANSVERSE INSTABILITY



STREAMLINES ⟶ ATTACHMENT POINT A SEPARATION POINT S

SOURCE (ALLEN, 1969)

FIG. 13

rotation in adjacent vortices. By necessity this must be the case in order to eliminate excess shear along converging streamlines (Allen, 1969). Where the vortices converge in a descending motion zones of increased shear at the bed exist. Where they merge and ascend from the bed zones of decreased shear are found. Adjacent descending vortices, therefore, become zones of erosion aligned parallel to the mean flow direction, thus creating troughs. Ascending vortices become zones of deposition.

In the experimental section of his study Allen found that the wavelengths of the features were related to relative roughness and Froude number of flow by the empirical formula

$$\frac{\lambda x}{\lambda z} = 6.4\left(\frac{\overline{H}}{\overline{d}} \cdot Fr.\right)^{.27}$$

where (λ_x) is the mean streamwise wavelength, (λ_z) is the mean spanwise wavelength, $\overline{H}$ is the mean ripple height, $\overline{d}$ is the mean flow depth and Fr. is the Froude number based on mean flow depth and velocity (Allen, 1969).

Allen summarized the relationship of the features:

> "As measured over whole trains of ripples the following properties tend to grow in variance with decrease of flow depth and increase of flow speed: 1) streamwise wavelength (λ_x); spanwise wavelength (λ_z); and ripple height. The maximum dip azimuth (θ) of the ripple slip face also increases in variance with increasing rigour of flow conditions. The ripples lose regularity and simplicity of form as the Froude number and relative roughness of flow are increased" (Allen, 1969, p. 92).

The origins of the spanwise instability are most probably related to centrifugal instability. Since the bed form is three-dimensional "... it is logical to assume three-dimensionality for the flow, in which case spiral flows must, from continuity, be combined with the basic motion" (Allen, 1969, p. 92).

Relation of Spanwise Bed Forms to Glacial Flutings

In the science of geomorphology recourse must often be taken to relate different features on the basis of certain similar characteristics. The shape of drumlins, cited in Chapter One, has been compared to an egg shape, aircraft wings and the shapes of fish and aquatic mammals. The streamlined forms observed in these objects, all of which are subject to movement within a medium, have led to the belief that the drumlin shape is a "form-response" to the moving ice (Chorley, 1959). Allen (1969) saw similarities between spanwise ripples and certain kinds of larger dunes created in air and water. There are similarities between spanwise ripples and flutings in terms of both form and the presence of a regular spacing.

The fact that the spanwise ripples were created by a helicoidal kind of flow now seems certain. On the basis of similar form and the phenomenon of a wavelength it would seem possible that flutings were also the result of a helicoidal kind of flow acting in the basal ice layers.

Gravenor and Meneley (1958) suggested that an alternating series of high and low pressure zones were present in the basal layers of ice and were responsible for the formation of the flutings. Fig. 14-A illustrates the method of formation suggested by Gravenor and Meneley. Fig. 14-B represents the cross-profile of the helicoidal flow responsible for the formation of the spanwise ripples. By combining the two diagrams (Fig. 14-C) the suggested method of formation of the flutings is apparent. The zones of high pressure (Gravenor and Meneley, 1958) correspond to the attachment points of Allen (1969). Low pressure zones, conversely, correspond to the separation points.

SIMILARITIES BETWEEN SPANWISE INSTABILITY

AND HIGH AND LOW PRESSURE AT THE BASE OF ICE

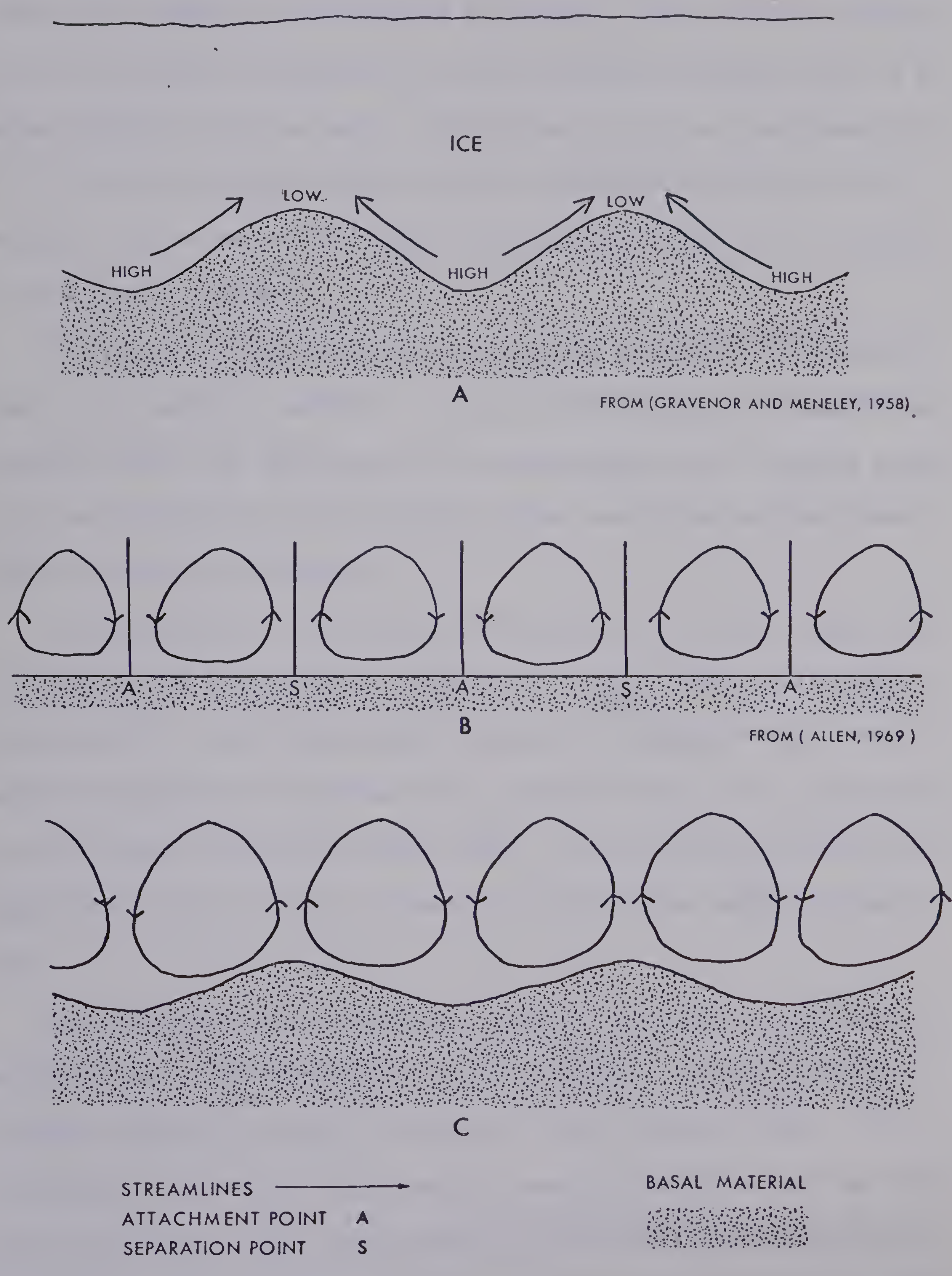


FIG. 14

Composite Flow in Ice

The flow patterns postulated for ice may be termed "composite flow" (Pers. Comm., W. Harrison). The kinematics of this kind of flow within ice, however, are difficult to conceive. As ice is non-Newtonian, it would not be expected to react to pressure differentials in a manner similar to air or water. Flow rates in ice are considered to be too low for inertial forces to have any appreciable effect on its movement, and no doubt this kind of flow pattern would not be visible in present day glaciers.

The method of investigating the possible occurrence of composite flow in ice would be twofold: 1) theoretical reasoning of some of the possible causes for the flow; and 2) examination of the internal structures and composition of the fluting ridges and of the supposed wavelengths across the flutings.

Investigation of the internal structures, mainly with respect to the orientation of pebbles at selected till fabric sites, was readily accomplished by the field methods discussed in Chapter Three. The dynamics and physics of the flow in ice itself, however, are quite complex and beyond the scope of this study. It is possible, however, to suggest situations in which a composite kind of flow might have existed.

The dissimilarities between the flow of water and ice necessitate modifications of the hypotheses of Allen (1969). Ice moves solely in a laminar fashion and Allen's work was in the turbulent phase. Also, a streamwise bed form is not produced beneath glacial ice and the flow pattern producing these features may be eliminated from consideration here. The problem, therefore, becomes one of creating a situation in

which a composite flow may be formed.

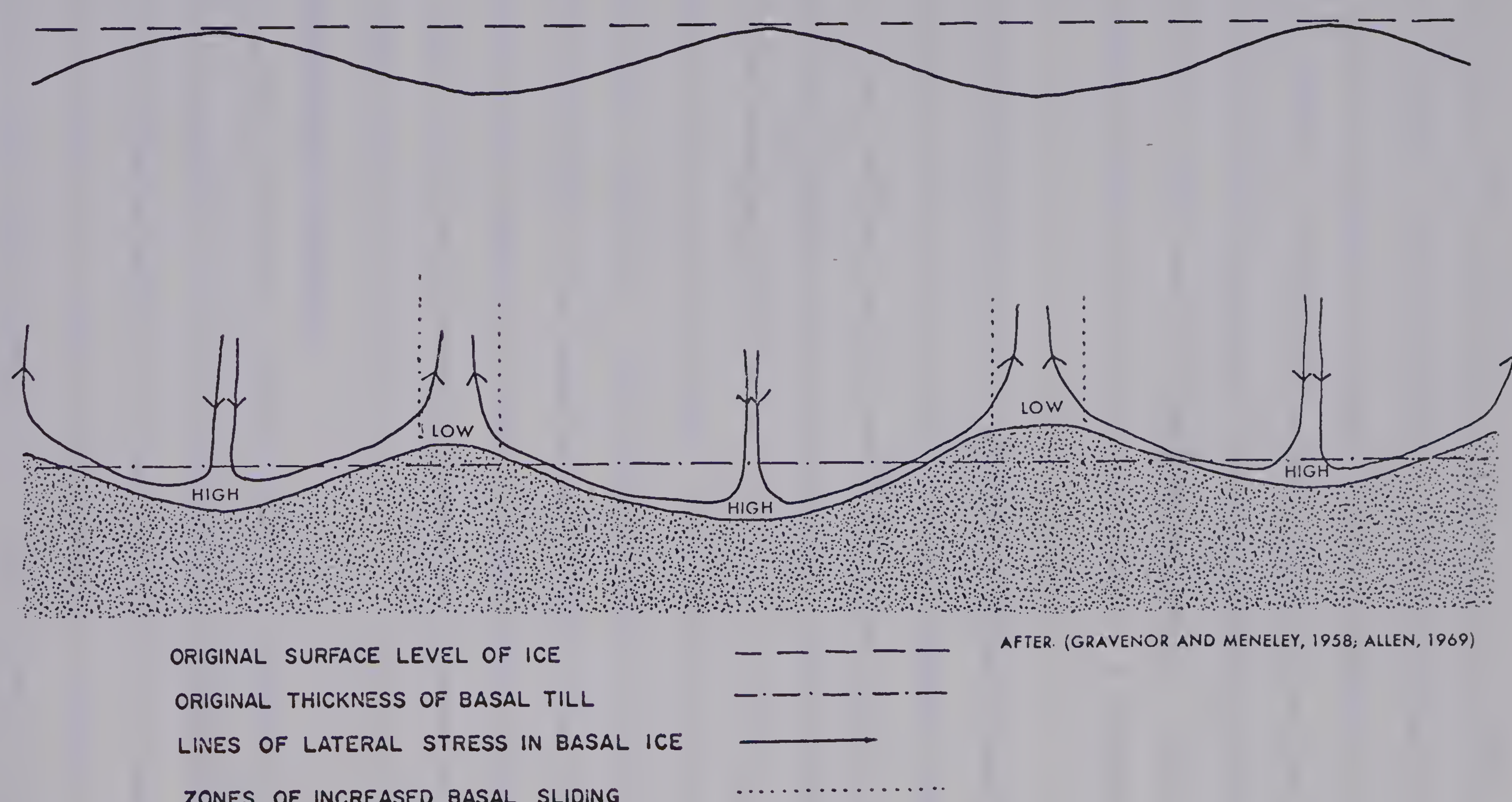
It is believed that composite flow might be induced by a variance in pressure at the base of ice. One possible method of creating varying pressure regimes at the base of ice would be by varying the thicknesses of ice above these regions. A decrease in the thickness of ice would result in a decrease in the stress at the base. Decreasing thicknesses could be due to increases in the rate of basal melting which would increase the basal sliding rate. Fig. 15 illustrates how a change in the thickness of the ice would result in a change in the shear stress at the base. Alternating zones of stress, in a two-dimensional sense, could thus be created and would be oriented perpendicular to the direction of regional stress.

In order for the ice to return to an equilibrium situation where surface slope is uniform a transverse movement of ice must occur. Stress must be exerted outwards from beneath the greater thicknesses of ice into the zones of thinner ice. A vertical component of movement and stress, therefore, must exist in the regions of thinner ice in order to raise the surface level of the thin ice.

The foregoing illustration assumes only lateral and vertical stress and movement are involved. This would be indicative of stagnant ice conditions. Flutings, however, are considered to be an active ice feature. The ice has a forward component and a longitudinal stress must be considered. The combination of longitudinal, lateral and vertical stresses would yield a composite kind of flow moving parallel to the regional line of ice movement.

Assume ice is moving past some point with a constant discharge. This can be represented by

POSSIBLE ORIGIN OF HIGH AND LOW PRESSURE ZONES



AFTER (GRAVENOR AND MENELEY, 1958; ALLEN, 1969)

FIG. 15

$$Q=\overline{A}\cdot\overline{V}$$

where (Q) is discharge, ($\overline{A}$) is mean cross sectional area and ($\overline{V}$) is the velocity of movement. If the velocity in a vertical column of ice increases the area must decrease. The shear stress at the base of the column must also decrease. If this situation is repeated in directions transverse to the line of ice movement a series of decreasing and increasing stress levels would result at the base of the ice. The resultant motion within the basal ice layers should be one of a composite kind of flow.

It is not believed, however, that a complete rotation of each helix about a horizontal axis would occur if the above situation existed. If complete rotations occurred, material would be carried high up into the ice and would be distributed about the flow lines. Once the flow ceased and material subsequently melted out of the ice no flute-like features composed of till would be expected. No return flow at the upper levels can occur, therefore. This hypothesis may be related to a kind of isostasy principle. The upward movement of ice above the low pressure zones would relieve the stresses exerted by the adjacent high pressure zones. Once the distorting stresses are relieved no further movement would occur in the helices.

Response of the Subglacial Material

If the above kind of secondary motion occurred in the basal ice layers it should be possible to test the hypothesis by examining the nature of the flute-ridge materials. The fact that flutings of nearly identical form are found in crystalline bedrock and till strongly suggests that the ice itself played a major role in their formation (Gravenor and Meneley, 1958; Aranow; 1959).

The case for bedrock flutings seems straight-forward: the trough areas were carved when increased levels of stress, due to composite flow, had occurred. The material from the trough areas was removed with little or no redeposition of the eroded debris in the area. Those flutings composed of till present a different problem. The ridges may be depositional features, deposited there after material was transferred obliquely from the trough areas. They may also be erosional features, as in the case of the bedrock flutings.

If the till flutings are erosional features no variations in the fabric orientations of pebbles should be noted. Orientations parallel with the previous line of ice movement would be expected regardless of the position of a till fabric site with respect to a crest. The possibility of reorientation of a pre-existing fabric by overriding ice will be considered in Chapter Five.

The flutings, however, may be depositional, in which case the debris-rich basal layers moved from the troughs outwards to the adjacent ridges. As deposits of basal till tend to illustrate pebble orientations parallel to the line of ice movement the pebbles within the till matrix on the flanks of the ridges should trend in towards the crests from the up-glacier direction on either side of the crest. This would indicate that the basal ice above the flutings was moving obliquely to the trend of the ice, but in a systematic manner governed by the composite flow. These problems, plus the possibility of a wavelength across the flutes, are to be considered in Chapter Five.

Summary

An attempt has been made to relate ice and water flow on the basis of a similar kind of feature produced in each medium. Elongated span-

wise ripples were shown to be formed by a series of corkscrew vortices acting in the lower depths of water in a flume tank (Allen, 1969). Glacial flutings are a similar kind of feature in that they are elongated features with respect to the line of ice movement. A theoretical method of creating a situation in glacial ice where a similar kind of flow might be expected has been suggested.

CHAPTER FIVE

ANALYSIS OF TILL FABRIC, FLUTE PROFILE AND SEDIMENT DATA

Introduction

The hypothesis has been put forward that flutings were formed as a result of a composite flow in ice. The possibility of this kind of flow acting in the basal ice layers was initially suggested because of the similarity of form between small scale current ripples and flutings. Literature concerning this kind of flow in ice was unavailable prior to this study. The field methods used in the investigation, therefore, were designed to test the above hypothesis.

Analysis of Macrofabric Data

The first step in the analysis is to determine whether or not the fluting ridges are erosional or depositional features. If they are erosional features no consistent shift in the fabric orientations would be expected regardless of the placement of till fabric sites across the flute crests. The preferred orientations of pebbles would be the same as the original depositional pattern. If they are depositional features, according to the theory of composite flow, preferred orientations of pebbles along the flanks of the flutes should be oblique to the flute axes. Furthermore, the plunge of the long axes of pebbles is expected to be up-glacier, into the trough areas.

It is possible that preferred orientations of pebbles could be oblique to the flute axes and the features would not necessarily be depositional features. Ramsden and Westgate (1971) have presented evidence for reorientation of till fabrics by shearing of overriding ice.

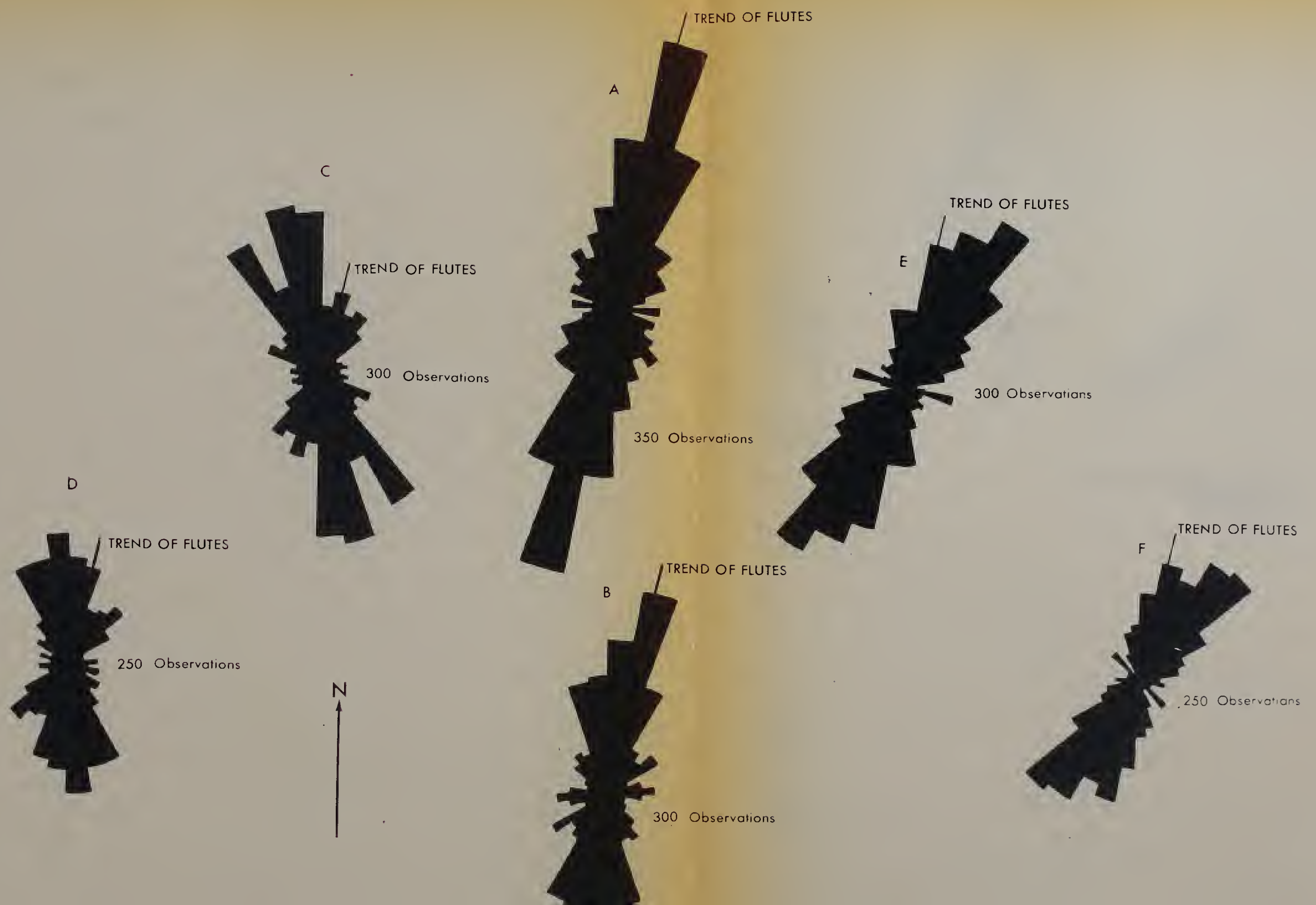
They found that in those sites where a reoriented fabric was suspected bimodal distributions of pebble orientations were found. One mode corresponded to the pre-existing fabric orientation and the second mode corresponded to the line of readvancing ice. It is possible that the flutes were formed by erosion of previously deposited till and that any oblique fabrics were produced by reorientation. If reorientation occurred, then previous work (Ramsden and Westgate, 1971) indicates that a bimodal distribution should occur, with one consistent mode parallel to the line of ice movement from which the till was originally deposited.

Examination of the data given in the Appendix illustrates that the distribution of preferred orientations expected under the composite flow hypothesis is observed. Fabric sites "C" and "D", located to the west of the crests, have preferred orientations from the NW-SE quadrants. Sites "E" and "F", located to the east of the crests, have preferred orientations in the NE-SW quadrants.

According to the composite flow hypothesis sites from similar positions on the fluting ridges should show similar orientation patterns with respect to the alignment of the flute crests. Therefore, orientation observations from similar sites have been combined into a composite diagram (Fig. 16). A clear pattern is immediately evident. The depositional pattern of the pebbles along the flanks of the flutes is one of an outward flare, away from the trend of the flutes in an up-glacier direction. This provides strong evidence for the depositional theory for the origin of the fluting ridges and for the concept of composite flow in ice.

It has been suggested that pebbles may become reoriented by the

COMPOSITE DIAGRAMS OF MACRO FABRIC SITES



shearing force of overriding ice (Ramsden and Westgate, 1971). Examination of the diagrams, however, reveals no consistent secondary mode. It is believed, therefore, that the orientation pattern is inherited from a composite flow in the basal part of the glacier.

<u>Statistical Treatment of the Macrofabric Data</u>

A concept concerning the degree of uniformity of process in the deposition of the till comprising the ridges was derived from the macrofabric data. Following Steinmetz (1962), a vector mean orientation ($\overline{A}$) was determined for each site. The pebble observations are assumed to represent vectors (Watson, 1956). Observations (N) numbering fifty pebbles were obtained as discussed in Chapter Three. Where possible an adjusted vector mean orientation ($\overline{A}_1$) was also determined. The calculation of $\overline{A}_1$ differs slightly from that of $\overline{A}$ in that the modal sector of each contour diagram (See Appendix) is isolated and the mean of these observations is calculated. Calculation of $\overline{A}_1$ eliminates the vector components of transversely oriented pebbles and a figure more representative of the mode results. This method is restricted if the data are scattered throughout the diagram as it becomes difficult to isolate a representative mode.. The data are given in Table 2.

The magnitude of the resultant vector (R) is also given in Table 2. When all pebble observations are congruent, R=N. The confidence limit ($\theta°$) is given in Table 2 and with each contour diagram in the Appendix. $\theta°_{.05}$ is defined as the "... probability that the true direction of cross-bedding (resultant of the population sampled) deviates more than $\theta°$ degrees in direction from the calculated resultant direction of cross-bedding (resultant of the population sampled) is 5 per cent" (Steinmetz, 1962, p. 806). The value of $\theta°$ is dependent on the disper-

TABLE 2

ORIENTATION DATA FOR MACROFABRIC SITES

SAMPLE SITE	N[1]	$\overline{A}$[2]	$\overline{A}_1$[3]	R[4]	%SIG. R[5]	$\theta^\circ_{.05}$[6]	K[7]
1-A	50	20.9°	19.1°	25.9	1.0	20°	2.03
2-A	50	159.3°	----	16.7	1.0	29°	1.47
3-A	50	13.8°	----	19.9	1.0	25°	1.63
4-A	50	4.1°	16.3°	31.9	1.0	15°	2.70
5-A	50	3.1°	6.8°	39.6	1.0	10°	4.79
6-A	50	148.8°	----	18.8	1.0	26°	1.57
7-A	50	20.3°	----	28.2	1.0	18°	2.45
1-B	50	354.7°	1.0°	23.7	1.0	22°	1.87
2-B	50	128.2°	----	15.1	1.0	31°	1.41
3-B	50	17.1°	9.3°	29.9	1.0	17°	2.43
4-B	50	2.0°	4.4°	27.1	1.0	19°	4.39
5-B	50	355.7°	5.8°	31.1	1.0	16°	2.60
6-B	50	211.3°	----	20.8	1.0	24°	1.68
1-C	50	349.5°	343.4°	38.8	1.0	11°	4.39
2-C	50	166.8°	----	19.7	1.0	25°	1.62
3-C	50	327.7°	323.7°	33.7	1.0	14°	3.00
4-C	50	340.1°	338.7°	27.4	1.0	19°	2.16
5-C	50	2.4°	1.6°	39.9	1.0	10°	4.86
6-C	50	138.7°	----	21.8	1.0	23°	1.74
1-D	50	356.1°	358.7°	31.3	1.0	16°	2.63
2-D	50	159.7°	----	13.8	1.0	32°	1.36
4-D	50	10.9°	----	28.2	1.0	18°	2.25
5-D	50	354.3°	352.2°	30.5	1.0	16°	2.51
6-D	50	76.7°	----	19.6	1.0	26°	1.61
1-E	50	62.3°	61.3°	37.0	1.0	12°	3.77
2-E	50	225.9°	----	14.0	1.0	33°	1.36
3-E	50	15.3°	16.3°	26.0	1.0	20°	2.05
4-E	50	7.9°	----	23.2	1.0	22°	1.83
5-E	50	24.1°	24.1°	32.6	1.0	15°	2.81
6-E	50	37.6°	----	33.3	1.0	14°	2.94
1-F	50	48.9°	42.6°	31.7	1.0	15°	2.67
2-F	50	191.4°	----	21.4	1.0	24°	1.71
3-F	50	16.1°	29.2°	22.3	1.0	23°	1.77
4-F	50	10.9°	23.3°	28.1	1.0	18°	2.24
5-F	50	19.3°	26.3°	34.5	1.0	14°	3.15

[1] N number of pebble observations
[2] $\overline{A}$ vector mean orientation
[3] $\overline{A}_1$ adjusted vector mean orientation
[4] R magnitude of resultant vector (See Watson, 1956)
[5] %SIG. R percentage significance of R (See Watson, 1956)
[6] $\theta^\circ_{.05}$ confidence limit at 5% probability level
[7] K estimate of precision

sion of data points around $\bar{A}$. Strong pebble orientations yield small values of $\theta°$ while dispersed orientations yield large values of $\theta°$.

An estimate of the precision parameter (K) is also given in Table 2. K is determined for each fabric site by

$$K = \frac{N-1}{N-R}$$

where the degrees of freedom equal 2(N-1). It can be seen that K is dependent upon the magnitude of R.

Manipulation of K values for similar fabric sites was undertaken to determine if one mean orientation ($\bar{A}_2$) could be found for similar fabric sites. This homogeneity of variance test (Steinmetz, 1962) is tested by maximum F-ratio. For each set of similar fabric sites the largest K is divided by the smallest K. The results were compared with tabled values (Pearson and Hartley, 1954). "The null hypothesis states that the sample precision parameters (K) are independent estimates of the same population parameters (K)" (Steinmetz, 1962, p. 809). If this hypothesis is not rejected at the appropriate significance level, one per cent, analysis may proceed. The results of this test are given in Table 3.

TABLE 3

HOMOGENEITY OF VARIANCE TEST

Sites "A"	K-max/K-min = 3.2576	Insig.$_{.01}$
Sites "B"	K-max/K-min = 1.8468	Sig.$_{.01}$
Sites "C"	K-max/K-min = 3.0019	Sig.$_{.01}$
Sites "D"	K-max/K-min = 1.1987	Sig.$_{.01}$
Sites "E"	K-max/K-min = 2.7696	Sig.$_{.01}$
Sites "F"	K-max/K-min = 1.8328	Sig.$_{.01}$

The next step in the analysis is to compute a resultant vector (R_1) for each similar fabric site. Sample sites "A", however, can not be grouped into one new set of data because the maximum F-ratio is greater than the accepted value at the one per cent level. The rejection of the "A" sites can be explained due to the inclusion of the data from flutes 2 and 6, which as Table 2 illustrates, have $\bar{A}$ values that are unrepresentative. These two flutes also show consistently low K values. Therefore, it was decided to re-test the maximum F-ratio after eliminating the data from flutes 2 and 6 altogether. The adjusted results are given in Table 4.

TABLE 4

ADJUSTED HOMOGENEITY OF VARIANCE TEST

Sites "A"	K-max/K-min = 2.9942	$\text{Sig.}_{.01}$
Sites "B"	K-max/K-min = 1.3904	$\text{Sig.}_{.01}$
Sites "C"	K-max/K-min = 2.2430	$\text{Sig.}_{.01}$
Sites "D"	K-max/K-min = 1.1680	$\text{Sig.}_{.01}$
Sites "E"	K-max/K-min = 2.0607	$\text{Sig.}_{.01}$
Sites "F"	K-max/K-min = 1.1786	$\text{Sig.}_{.01}$

All samples now are significant at the one per cent level and a composite resultant vector may be computed using the same procedures as for the individual fabric sites.

The final step is to show that the R_1 values for the combined samples are identical to the similar sites from which they were derived. The formula (Steinmetz, 1962) is

$$F = \frac{(N-q)}{(q-1)} \cdot \frac{\Sigma R - R_1}{N - \Sigma R}$$

where

N total number of unit vectors
q number of samples under consideration
ΣR sum of R values for similar fabric sites
R_1 combined value for N observations
p number of dimensions

The computed F values for the combined sites are compared with any standard F table with the following degrees of freedom

$$d.f. = (p-1)(q-1)/(p-1)(N-q)$$

The null hypothesis states that the resultant vectors of q fabric sites are drawn from the same population. If this is not rejected one resultant vector may be calculated for similar fabric sites. The results of this test are given in Table 5.

TABLE 5

COMPOSITE ORIENTATION DATA FOR FLUTES 1, 3, 4 and 5

SITES	N[1]	F-VALUE	d.f.	$\overline{A}_2$[2]	R_1[3]	%SIG.R_1[4]	$\theta°$[5]	K[6]
"A"	250	.18	8/490	11°	145.8	1.0	7°	2.39
"B"	200	1.61	6/392	3°	109.6	1.0	9°	2.20
"C"	200	2.65	6/392	345°	136.6	1.0	7°	3.14
"D"	150	.61	4/394	0°	89.5	1.0	9°	2.46
"E"	200	4.51	6/392					
"F"	200	2.24	6/392	26°	113.7	1.0	9°	2.31

[1]N the number of pebble observations
[2]$\overline{A}_2$ composite mean orientation
[3]R_1 combined value for N observations (See Watson, 1956)
[4]%Sig.R significance level of R (See Watson, 1956)
[5]$\theta°$ confidence limit
[6]K estimate of precision

The F value for sites "E" is 4.51, which is insignificant at the one per cent probability level. A mean orientation ($\overline{A}_2$) may not be computed to represent this group of fabric sites. The remaining five

composite sites have significant F values and a valid $\bar{A}_2$ value has been calculated for each sample.

The orientations listed are representative of what is expected from the composite diagram (Fig. 16). Orientations at sites "D", however, should deviate from the crest alignment by a greater angle than those at sites "C". The composite diagram modes indicate that this expected relationship is reversed.

Analysis of Microfabric Data

Rose diagrams of the two-dimensional trends and plunges for ten selected fabric sites are presented in Fig. 17. The statistical analysis of the microfabric data is different from that of the macrofabric data. The orientations of fine particles in thin section can be viewed only two-dimensionally and, therefore, three-dimensional statistical methods can not be employed. A test used to determine the significance of two-dimensional orientations is the Chi-square (χ^2) test (Andrews and Smithson, 1966). Although the χ^2 test does not yield a two-dimensional mean orientation, it does determine whether or not a two-dimensional distribution of pebble long axes differs significantly from a uniform two-dimensional distribution. χ^2 is determined by the formula

$$\chi^2 = \frac{\Sigma(fo-fe)^2}{fe}$$

where fo is the number of observations per 10° sector, fe is the expected number of observations per 10° sector in a uniform distribution. The degrees of freedom are determined by (N-1), where N refers to the number of 10° sectors chosen. 18 sectors in a 180° distribution were chosen for each microfabric diagram. The results are compared with tabled χ^2 values and the appropriate significance levels may be determined.

MICROFABRIC DIAGRAMS FOR SELECTED SITES

The modal 30° sector for each horizontal plane was determined visually and the mean orientation for each diagram was assumed to be at the center of this 30° sector. Analysis of the orientations in the vertical plane oriented parallel to north involved determining the percentage of apparent up-glacier and down-glacier plunges for each slide. The data are presented in Table 6.

TABLE 6

ORIENTATION DATA FOR SELECTED MICROFABRIC SITES

SITE	N	(χ^2)	SIG. LEVEL	$\bar{A}$ OF 30° MODE	%PLUNGE[1]	%PLUNGE[2]
2-C	69	63.6	1.0	335°	49.4	50.6
2-D	95	28.6	5.0	335°	55.6	44.4
2-E	83	18.1	Insig.	55°	36.3	63.7
5-A	158	62.2	1.0	15°	59.6	40.4
5-C	101	37.3	1.0	335°	62.1	37.9
5-F	109	54.3	1.0	55°	71.0	29.0
6-A	105	40.1	1.0	---	71.1	28.9
6-B	73	27.4	10.0	25°	33.0	67.0
6-D	110	21.7	Insig.	75°	36.2	63.8
6-E	73	19.5	Insig.	85°	51.5	48.5

[1] %PLUNGE refers to the up-glacier plunges

[2] %PLUNGE refers to the down-glacier plunges

It can be seen that the microfabric orientations (Fig. 17) are more dispersed than the corresponding macrofabric orientations (See Appendix). The same basic pattern, however, is exhibited by both the microfabric and macrofabric orientations. Sites 6-D and 6-E have modal 30° sectors that are inconsistent with the macrofabric diagrams. Several possible

explanations exist for these discrepancies. Microfabric orientations can differ from macrofabric orientations due to frost disturbance of the fine and coarse particles, due to transverse orientations, or due to the accidental creation of long axes during the preparation process of the slide. It is also possible that the fine particles have more freedom of movement during deposition. It can not be determined which of these factors is responsible for the absence of parallelism in some of the microfabric orientations with the macrofabric orientation mode observed.

Site 6-D shows a very poor macrofabric and microfabric orientation. The till at this site may have been disturbed subsequent to deposition or a well-developed orientation may not have existed there at all. It is possible that an orientation may have existed in the glacier ice which was subsequently destroyed during the process of deposition.

The microfabric values of plunge at each site indicate moderate angles of plunge both up-glacier and down-glacier. The majority of the plunges, however, reveal a predominant direction of plunge. Sites 2-C-b and 6-D-b, however, show a predominance of particles with a down-glacier plunge.

Spectral Analysis

Gravenor and Meneley (1958) presented evidence of a preferred spacing, or wavelength (λ), across fluting fields in Alberta and Saskatchewan (Fig. 10). Their method of determining fluting wavelengths was to measure distances directly from air photographs. This method results in the exclusion of many of the smaller flutings. A more sophisticated technique, employing spectral analysis of instrumentally surveyed traverses, was used.

Spectral analysis ia a technique that may be applied to the study of periodic or rhythmic data. It has been used in research in physical geography and meteorology to study the periodicity of landforms (Preston, 1966) and meteorological phenomena (Rayner, 1971). Briefly, it may be considered to employ principles similar to that of a spectrum, whereby data are broken down into their component parts and relevant information is separated from extraneous material. Spectral analysis allows for the examination of data in an exacting, but mathematically complex, manner by filtering out "noise", or random data. Owing to the hierarchy of flute sizes it was thought that characteristic wavelengths could best be obtained by statistical rather than purely subjective methods.

In analyzing the occurrence, or recurrence, of some phenomena against time or distance sine curves, or sine-generated curves, are used. The sine curves are fitted and re-fitted to the original data in an attempt to detect any wavelengths involved.

Traverses were instrumentally surveyed to provide data necessary for analysis of the flutings in terms of a wavelength. The two traverses are plotted in Figs. 8 and 9. No pronounced wavelength is evident in either traverse. The technique of spectral analysis, therefore, was used to detect any hidden wavelengths which might exist.

Analysis of Spectral Data

Several factors and parameters need to be defined prior to examining the data and the results. The number of data points (n) used in each traverse must be known. The data points refer to the number of equally spaced height readings taken from each traverse. Measurements were taken at fifteen meter intervals from each traverse. By choosing

this short an interval a significant number of points have been taken from even the shortest wavelengths. Unless short intervals are taken wave forms with small wavelengths will be misrepresented in the data.

The number of lags chosen for each traverse must also be known. A lag (m) is defined as a difference in time (distance) of two events or values considered together (Blackman and Tukey, 1958). Alternatively, one may consider that the original wave form is displaced a distance corresponding to the spacing of each data point (n). For each traverse the displacement of the first lag is 1 x 15 =15 meters, for the second lag, 2 x 15 =30 meters, and so forth up to the maximum number of lags for each traverse.

The resultant graphs for the spectral analysis of each traverse are presented in Fig. 18. The abscissa of each graph represents frequency interval, or wavelength (λ). The ordinate is the power (variance) spectral estimate. A power (variance) spectral estimate is defined as the contribution to the total sample variance (σ^2) within corresponding frequencies (Pers. Comm., K. Hage). The area beneath the curve in each graph, in variance units, represents the total sample variance. Selected frequencies, therefore, contribute a certain amount of variance to the sample variance. The term "estimate" is used because the data under consideration represent a finite portion of the total available data.

Determining the area beneath curve is relatively inaccurate. It may be determined by the summation of the multiplication of each power spectral estimate by the corresponding frequency. This procedure is continued throughout the range of frequencies involved.

An exception occurs in this procedure and a minor adjustment is needed. The longest frequencies occur at .000 cycles/meters, which rep-

GRAPH OF POWER SPECTRAL ESTIMATES VS. FREQUENCY (CYCLES/METERS)

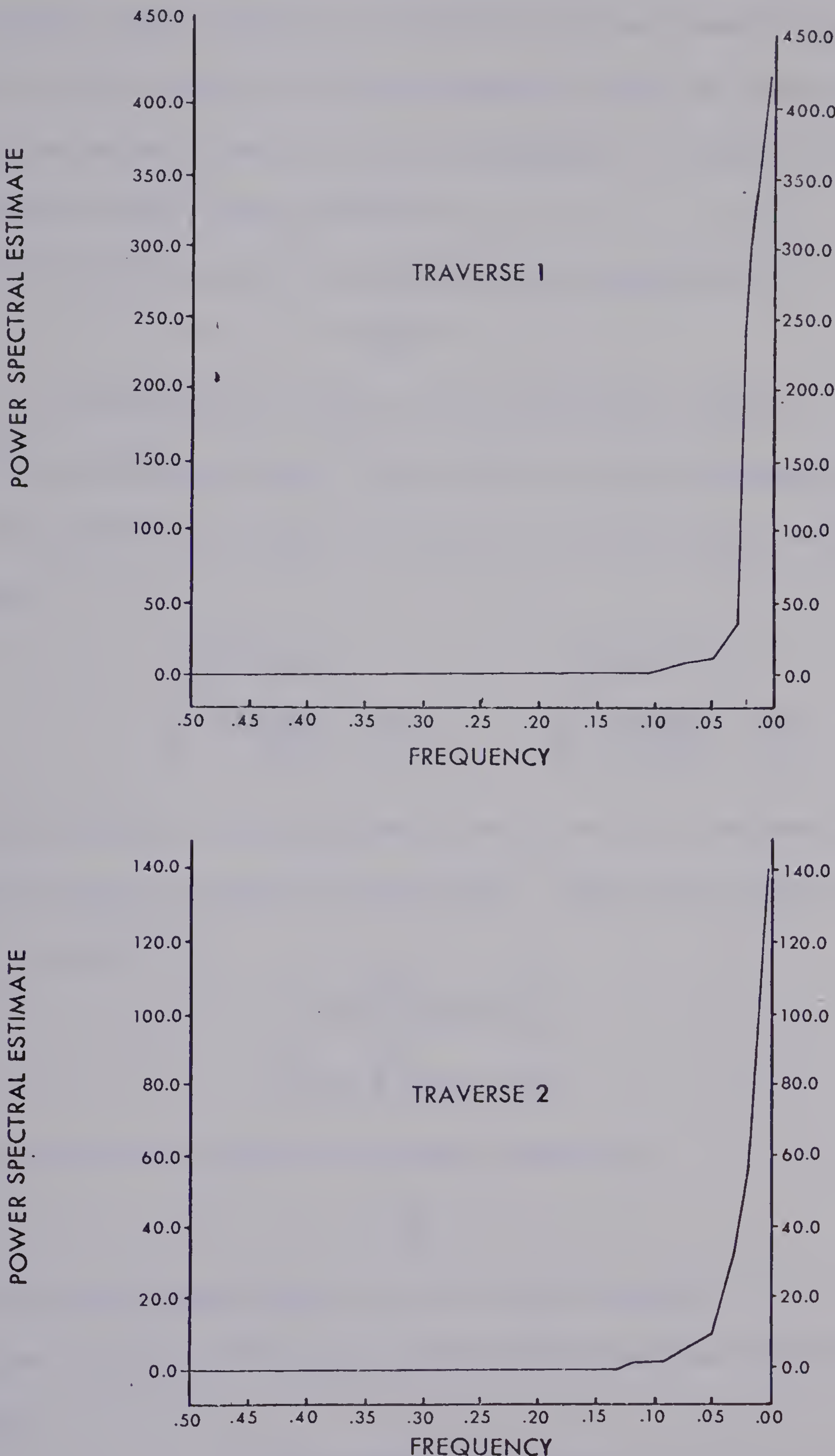


FIG. 18

resents an infinitely long wavelength. For this frequency the power spectral estimate is multiplied by one half the frequency interval of the abscissa. For example, the abscissa for the graph of Traverse 1 (Fig. 18) is in units of .017 cycles/meters. For the lowest frequency multiplication would be by .0085 cycles/meters. If this is not done the variance would become infinite.

The determination of λ is solved by the equation

$$\lambda = \frac{1}{x} \cdot m$$

where x is the frequency value at each significant point.

σ^2 for Traverses 1 and 2 are 55.857 and 21.365 respectively. The σ^2 is divided by the number of lags used in the spectral analysis of each traverse.

Traverse 1	Traverse 2
$\frac{\sigma^2}{m} = \frac{55.875}{30} = 1.862$	$\frac{\sigma^2}{m} = \frac{21.365}{50} = .427$

The ordinates of Fig. 18 are rescaled so that the above corresponding values equal one unit on each graph. Using this scale confidence limits are given by

$$\text{Prob}\left(\frac{\chi^2}{\gamma} < X\right) = 95\%$$

$$\text{Prob}\left(\frac{\chi^2}{\gamma} < Y\right) = 5\%$$

where γ equals the degrees of freedom, given by

$$\gamma = \frac{2n}{m}$$

which is approximately equal to 20 for each traverse.

From a table of χ^2 values appropriate values are substituted in the equation

$$\text{Prob}\left(\frac{10.8508}{20} < X\right) = .5425$$

$$\text{Prob}\left(\frac{31.4104}{20} < Y\right) = 1.5705$$

Horizontal lines are drawn on Fig. 18 at these corresponding probability levels on each graph. Any point on each graph which lies within these confidence limits has a probability of occurring by random chance more than 5% of the time and therefore is considered insignificant. Those points which lay above the 5% confidence limit are accepted as significant provided that the wavelengths are not excessive when compared to the total length of the traverse. The problem of the significance of long wavelengths will be discussed later.

A premise used in the analysis of the graphs of Fig. 18 is that of the "white noise spectrum" (Rayner, 1971). If the data used in the analysis were random, with no periodicity, this graph would produce a straight horizontal line above the abscissa, the "white noise spectrum." Any deviations from this line, however, may be interpreted as potentially significant of a wavelength at the corresponding distances involved. The significance of any such deviations, however, is dependent upon several factors to be discussed below.

Analysis of Resultant Wavelengths

Traverse 1 yielded insignificant points at the 5% probability level until a wavelength of over 400 meters occurred. All wavelengths longer than this also proved significant at the 5% level. Traverse 2 had a similar kind of spectrum (Fig. 18) and wavelengths of the same distances were found to become significant at the 5% level.

These long wavelengths correspond unfavorably with the data of Gravenor and Meneley, 1958; Fig. 10). Wavelengths of these distances are not represented in Fig. 10 as significant. Wavelengths at the expected distances of 90-120 meters (Gravenor and Meneley, 1958) are insignificant for both traverses.

It is believed that the excessively long wavelengths are also insignificant. Wavelengths of these distances are not examined a significant number of times in the spectral analysis and are believed to be unrepresentative of distinct wavelengths of consequence. The upward trend of each curve (Fig. 18) as frequencies become larger is common in many kinds of spectral analysis (Pers. Comm., K. Hage) and, therefore, the longer wavelengths are considered insignificant in this study.

The lack of any acceptable wavelengths in either set of data illustrates some interesting aspects concerning flutings. The method of examining the supposed wavelengths by instrumental survey and spectral analysis is more exacting than air photograph analysis and it indicates that a 90-120 meter wavelength is absent along the two traverses examined. Wavelengths of this magnitude, therefore, are not universal for fluting fields throughout Alberta.

The data indicate that no acceptable wavelength exists along either traverse, but it should not be interpreted that no wavelengths exist in any fluting field. The selection of the position of each traverse across the fluting ridges was limited by the location of suitably long roads. The concentration of flutings, therefore, may not have been representative of what exists in other sections of this or other fluting fields. It is possible that the longer wavelengths are significant, but for this study they could not be accepted. Accurate traverses spanning entire fluting fields are required before this aspect of fluting development can be resolved.

Sediment Analysis

The mechanical analysis procedures of the till samples were outlined in Fig. 4. Folk and Ward's (1957) statistics were employed for

the analysis of the sand samples from the flank of one ridge. This same technique, however, could not be employed in the statistical analysis of the particle size distributions of the till samples because the the cumulative curves were too open-ended and necessary percentages could not be obtained.

Krumbein and Pettijohn (1938) used two statistics which may be applied to the analysis of till, a median value (Q_2) and a sorting coefficient ($S_o = \sqrt{Q_3/Q_1}$). Q_2 is that particle size which lies on the 50% line of a cumulative curve. Q_1 and Q_3 are the first and third quartiles and are found at the 25% and 75% points on a cumulative curve. Q_2 is given in millimeters, but the S_o is a dimensionless number. A S_o value less than 2.5 indicates a well-sorted sediment. S_o values of approximately 3.0 indicate a normally-sorted sediment. S_o values greater than 4.5 indicate a poorly-sorted sediment. The Q_2 and S_o values for the till samples are given in Table 7, and the cumulative curves for each sample are given in Fig. 19.

The median values of the till samples tend to be concentrated in the fine sand to coarse silt range (.100mm-.040mm). Exceptions occur in flute 6, where coarser median values occur. Isolated deviations from this trend are found, but there is no consistent variation or trend either across the individual flute crests or along the entire length of the fluting field.

The S_o values are variable, but most show values indicating poorly-sorted sediments. Flute 6, located near the center of the northern sector of the fluting field, has very low S_o values, in the range of a well-sorted sediment. This is not indicative of a well-sorted sediment, however; only the central portion of the cumulative curves is considered

CUMULATIVE CURVES FOR TILL SAMPLES

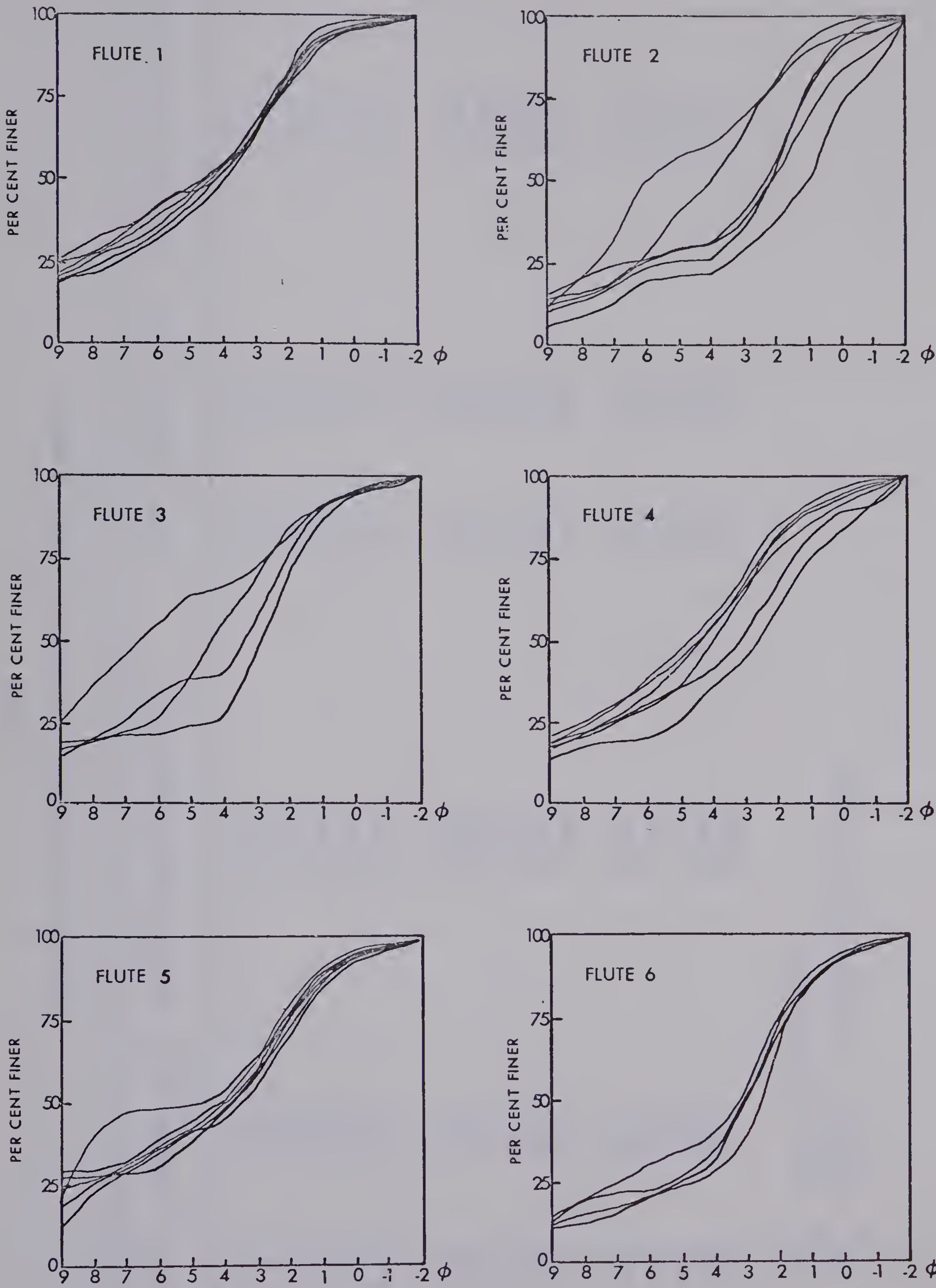


FIG. 19

TABLE 7

RESULTS OF MECHANICAL ANALYSIS OF TILL SAMPLES

FLUTE	MEDIAN (Q_2)[1]	SORTING COEFFICIENT (S_o)[2]	FLUTE	MEDIAN (Q_2)[1]	SORTING COEFFICIENT (S_o)[2]
1-A	.052	10.049	4-A	.073	7.176
1-B	.059	5.125	4-B	.065	4.451
1-C	.048	5.599	4-C	.177	3.939
1-D	.088	3.834	4-D	.042	5.838
1-E	.045	7.303	4-E	.117	7.269
1-F	.056	8.844	4-F	.110	6.897
2-A	.218	6.658	5-A	.073	-----
2-B	.068	4.618	5-B	.073	7.169
2-C	.016	5.908	5-C	.059	8.583
2-D	.141	3.611	5-D	.040	9.219
2-E	.163	6.230	5-E	.103	8.111
2-F	.221	4.338	5-F	.088	12.794
3-A	.141	2.303	6-A	.117	5.270
3-B	.052	3.556	6-B	.137	2.512
3-C	.007	-----	6-C	.147	2.357
3-E	.093	5.590	6-D	.139	-----
3-F	.011	8.860	6-E	.192	2.555

[1] Q_2 size in millimeters

[2] S_o $\sqrt{Q_3/Q_1}$, a dimensionless number

in the S_o.

It is concluded that no variation exists in the mechanical composition of the till which can be related to the position of the sample within the fluting field. This conclusion is in agreement with the findings of Gravenor and Meneley (1958) and Aranow (1959), who found that properties of the subglacial material were not responsible for the localization of flutings or drumlins.

Summary

The variations of preferred orientations of pebbles across flute crests have been found to illustrate the "herring-bone" pattern which was postulated in Chapter Four. The consistent pattern of pebble alignment from one flute crest to another provides evidence that composite flow had occurred in the basal ice layers at the time of formation of the flutings in the Athabasca area. Through statistical analysis (Steinmetz, 1962) it was possible to obtain mean orientations for all grouped similar fabric sites (Fig. 16), except fabric sites "E". The composite diagram of macrofabric sites shows that pebble orientations consistently trend in towards the flute crests from along the flanks of the ridges. Microfabric orientations in most cases have been found to illustrate the same kind of pattern as the corresponding macrofabric diagrams.

A sophisticated technique, employing spectral analysis, was applied to the data from Traverses 1 and 2 (Figs. 8 and 9). It was found that the 90-120 meter wavelength (Gravenor and Meneley, 1958; Fig. 10) was insignificant for both traverses. Long wavelengths, over 400 meters, were found to be significant at the 5% probability level, but were dismissed as insignificant in this study.

Till samples from each fabric site were analyzed (Table 7). It was

found that no consistent trends or variations exist across flute ridges or along the entire length of the field which might be attributed to the localization of flutes in the Athabasca area.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

Introduction

The aim of this study was to present a theory for the origin of glacial flutings. As drumlins and fluting ridges are considered to be a similar kind of glacigenic landform the initial step was to compare both features. Similarities were found to exist with respect to form, composition and orientation of the features with respect to the line of ice movement.

There are two main differences, however, that suggest fluting ridges and drumlins may be regarded as separate landforms. The differences are the extremely elongate nature of individual ridges and the fact that they appear to be spaced in a systematic manner. Many articles concerned with both large and small scale flutings have mentioned a regular spacing (Hoppe and Schytt, 1953; Gravenor and Meneley, 1958; Baranowski, 1970), but the distribution of drumlins within any one field seems to be random (Smalley and Unwin, 1968). Evidence has been gathered, however, which suggests that drumlins may have a preferred spacing (Reed, Galvin and Miller, 1962).

Theories for the Formation of Drumlins and Flutings

Previous attempts at accounting for the formation of drumlins may be categorized in two major schools, the depositional and erosional. The depositional theory (Alden, 1905, 1911; Hollingworth, 1931; Charlesworth, 1957) assumed that drumlins were the result of a localized plastering on, or accretion, of material from the debris-rich basal layers. The erosional theory (Tarr, 1894; Gravenor, 1953; Flint, 1957) assumed

that pre-existing deposits were re-moulded into the drumlin shape.

Flutings occur on both a large and small scale, but the theories presented for the small scale flutings are not applicable to the large scale flutings of western North America. Processes of basal squeezing or gouging may account for the formation of small scale flutings, but are not feasible mechanisms for the formation of large scale flutings. An alternative theory, therefore, is proposed to explain the formation of large scale flutings.

Gravenor and Meneley (1958) presented a theory which assumed that some process acting in the basal ice itself was responsible for the formation of the flutings. A series of high and low pressure zones aligned parallel to the line of ice movement were thought to have been created in the basal ice at equally spaced intervals. Material in the debris-rich basal ice layers was thought to have moved obliquely from beneath the high pressure zones into the adjacent low pressure zones. The fluting troughs, therefore, would have been formed beneath the high pressure zones. The fluting ridges would have been formed beneath the low pressure zones and would be composed of material originally found beneath the high pressure zones.

This study was partially designed to test the theory presented by Gravenor and Meneley (1958). The causes of a secondary kind of basal ice movement and how it operated in the basal ice layers remained to be examined.

Secondary Flow in Water

The mechanisms of a helicoidal kind of flow acting in water were examined in Chapter Four. It was found that longitudinal current ripples resembled the form, though not the scale, of flutings. Under cer-

tain flow conditions the current ripples were formed by a series of oppositely rotating spiral vortices oriented parallel to the flow direction. Adjacent descending vortices created an increase in shear along the surface of the loose-grain bed. Where the vortices separated from the bed the shear along the bed ceased and the grains were deposited (Allen, 1969). Individual vortices underwent complete rotations before the final current ripples were formed. The spacing of the ripples was found to be relatively consistent.

Composite Flow in Ice

The similarity of form, orientation and wavelength suggests that a similar kind of process may have operated during the formation of the flutings. This kind of flow in ice, however, was termed composite flow.

Glaciological literature concerning this kind of movement within ice was nonexistent. A theoretical situation in which a composite kind of flow could exist was suggested. If basal ice velocities in equally spaced zones beneath the glacial ice could be increased relative to the adjacent areas, possibly due to increased rates of basal melting, the thicknesses of ice above these areas would be expected to decrease. The shear stress levels, which are partly dependent on thickness of ice, would, therefore, decrease relative to the slower moving, thicker ice to either side. The stress differentials perpendicular to the line of regional ice movement would be expected to vary in a series of alternating high and low pressure zones. The resultant movement of basal ice necessary to attain a stress equilibrium situation would be from beneath the zones of high pressure to the zones of low pressure. This movement could resemble that given in Fig. 15.

It is not believed that complete rotatations of the composite flow regimes would occur. The debris-rich basal ice layers would move oblique-

ly towards the low pressure zones and this material would be deposited in the form of the fluting ridges beneath these zones.

Fabric Analysis and the Reconstruction of Flow Lines

Attempts were made to detect evidence for composite flow in the internal structure of the fluting ridges. Assuming parallelism of ice flow direction and pebble long axes, the pebbles along the flanks of the fluting ridges should show preferred orientations oblique to the trend of the flutings. The two-dimensional orientations should show a "herring-bone" pattern, the long axis orientations lying oblique to the flute crests. If such were the case it would provide strong evidence for the depositional theory for the origin of the fluting ridges and for the concept of composite flow in ice.

The long axis orientations were found to illustrate the postulated pattern (Appendix and Fig. 16). Statistical analysis, after Steinmetz (1962), showed that nearly all the fabric orientations from similar north-facing fabric sites could be grouped into one set of composite mean values. The exception to this procedure occurred at fabric sites "E". Flutes 2 and 6 were south-facing roadcuts and yielded poor orientations and they were excluded from the compsoite mean orientations. Therefore, it appears that a consistent ice flow direction dependent on the position relative to the flute crests can be detected. The pattern of flow direction inferred from the long axis orientations defines flow lines in accordance with the composite flow hypothesis.

Spectral Analysis of the Transverse Wavelengths

The second object of the study was to examine the supposed wavelengths across the flutings. Data presented by Gravenor and Meneley (1958; Fig. 10) suggest that a preferred spacing exists between adjacent

ridges. Gravenor and Meneley (1958), however, obtained data from air photographs with the result that many smaller flutings were excluded from the analysis. Detailed profile mapping, therefore, was undertaken to ensure that all flutes would be recorded.

The data were examined by spectral analysis (Dixon, 1968). Spectral analysis is an intricate method of analyzing periodic or rhythmic data. By using this kind of analysis detailed information concerning the lengths and significance of supposed wavelengths was examined.

Evenly spaced height readings were analyzed by computer and the resultant graphs of the analysis for both traverses are given in Fig. 18. The significance of any wavelength is determined by drawing confidence limits on each graph. The levels of significance chosen for the study were the 5% and 95% levels. The results for each traverse proved insignificant for the wavelengths quoted by Gravenor and Meneley (1958; Fig. 10).

The only wavelengths that proved significant were the long ones, over 400 meters for each traverse. These wavelengths are dismissed in this study as insignificant as their recurrence interval is too long considering the lengths of the two traverses examined. No wavelength of any consequence, therefore, can be said to exist along either traverse examined.

Textural Analysis of Till within Flutes

Analysis of the till samples gathered showed that the nature of the subglacial material was not important in the localization of the flutings in the Athabasca area. The composition of till, while not consistent with respect to percentages of sand, silt and clay, showed no variation or trend that could be related to the location of each

sample either across flute crests or along the length of the field.

It is believed, therefore, that the flutings were formed by a composite kind of flow acting in the basal ice layers. It is believed that the ridges are depositional features composed of material that was being transported in the debris-rich basal ice layers. While the present day knowledge of the physics of ice does not explain this hypothesis, the fabric orientations found agree with the concept of composite flow. The concept of evenly spaced composite flow regimes can not be accepted as valid along either traverse used in the study.

Suggestions for Further Study

More detailed work is needed on fabric orientations across flute crests and into the trough areas. Closely spaced sites should be examined across entire flute crests to analyze the degree of variation of orientation outwards from the center of the flute crest. Work is also needed on the possible relationships that may exist between the size of an individual fluting ridge and the degree of variance of orientation across the crest. As two ridges were found to resemble closely drumlins in the Athabasca area, true drumlins should be examined in a similar manner to see if pebble orientations vary in drumlins that are suspected as being depositional features.

More detailed, longer traverses are needed from several fluting fields to examine the possibility of an actual wavelength. It is possible that wavelengths may exist in other fields and profiles across entire flute fields should be used.

BIBLIOGRAPHY

Alden, W.C., 1905, "The Drumlins of Southeastern Wisconsin", United States Geological Survey Bulletin, No. 273, pp. 9-46.

Alden, W.C., 1911, "Radiation of Glacial Flow as a Factor in Drumlin Formation", Bulletin of the Geological Society of America, Vol. 22, pp. 733-734.

Allen, J.R.L., 1969, "On the Geometry of Current Ripples in Relation to Stability of Fluid Flow", Geografiska Annaler, Vol. 51-A, pp. 61-96.

Andrews, J.T. and B.B. Smithson, 1966, "Till Fabrics of the Cross-Valley Moraines of North-Central Baffin Island, Northwest Territories, Canada", Geological Society of America Bulletin, Vol. 77, pp. 271-290.

Andrews, J.T. and C.A.M. King, 1968, "Comparative Till Fabrics and Till Fabric Variability in a Till Sheet and a Drumlin: A Small Scale Study", Proceedings of the Yorkshire Geological Society, Vol. 36, pp. 435-461.

Aranow, S., 1959, "Drumlins and Related Streamlined Features in the Warwick-Tokio Area, North Dakota", American Journal of Science, Vol. 257, pp. 191-203.

Baranowski, S., 1970, "The Origin of Fluted Moraine at the Fronts of Contemporary Glaciers", Geografiska Annaler, Vol. 52-A, pp. 68-75.

Bayrock, L.A. and G.M. Hughes, 1962, "Surficial Geology of the Edmonton District, Alberta", Research Council of Alberta Preliminary Report, 62-6, 40 pp.

Blackman, R.B., and J.W. Tukey, 1958, The Measurement of Power Spectra, New York, Dover Publications Inc., 190 pp.

Boulton, G.S., 1968, "Flow Tills and Related Deposits on some Vestspitsbergen Glaciers", Journal of Glaciology, Vol. 7, pp. 391-412.

Boulton, G.S., 1970, "On the Deposition of Subglacial and Melt-out Tills at the Margins of Certain Svalbard Glaciers", Journal of Glaciology, Vol. 9, pp. 231-245.

Carol, H., 1947, "The Formation of Roches Moutonnees", Journal of Glaciology, Vol. 1, pp. 57-59.

Charlesworth, J.K., 1957, The Quaternary Era, with Special Reference to its Glaciation, 2 Vols., London, Edward Arnold Ltd., 1,700 pp.

Chorley, R.J., 1959, "The Shape of Drumlins", Journal of Glaciology, Vol. 3, pp. 339-344.

Cruden, D.M., 1966, Structural Analysis of part of the Brazeau Anticline, near Nordegg, Alberta, Unpublished M.Sc. Thesis, University of

Alberta, 107 pp.

Dixon, W.J., 1968, Biomedical Computer Programs, Berkeley and Los Angeles, University of California Press, Class T, No. BMD02T, pp. 459-483.

Dyson, J.L., 1952, "Ice-ridged Moraines and their Relation to Glaciers", American Journal of Science, Vol. 250, pp. 204-211.

Flint, R.F., 1957, Glacial and Pleistocene Geology, New York, John Wiley and Sons, 553 pp.

Folk, R.L. and W.C. Ward, 1957, "Brazos River Bar: A Study in the Significance of Grain Size Parameters", Journal of Sedimentary Petrology, Vol. 27, pp. 3-26.

Frye, J.C., H.B. Willman, M. Rubin and R.F. Black, 1968, "Definition of the Wisconsinan Stage", United States Geological Survey Bulletin, 1274-E, 22 pp.

Glen, J.W., 1958, "The Mechanical Properties of Ice, 1. The Plastic Properties of Ice", Philosophical Magazine, Supplement number 7, pp. 254-265.

Goldthwait, R.P., 1960, "Study of Ice Cliff in Nunatarssuaq, Greenland", United States Army Snow, Ice and Permafrost Research Establishment, Technical Report Number 39, 108 pp.

Gravenor, C.P., 1953, "The Origin of Drumlins", American Journal of Science, Vol. 251, pp. 674-681.

Gravenor, C.P. and W.A. Meneley, 1958, "Glacial Flutings in Central and Northern Alberta", American Journal of Science, Vol. 256, pp. 715-728.

Harris, S.A., 1969, "The Meaning of Till Fabrics", Canadian Geographer, Vol. 13, pp. 317-337.

Harrison, P.W., 1957, "A Clay-till Fabric: Its Character and Origin", Journal of Geology, Vol. 65, pp. 275-308.

Heidenrich, C., 1964, "Some Observations on the Shape of Drumlins", Canadian Geographer, Vol. 8, pp. 101-107.

Hollingworth, S.E., 1931, "The Glaciation of Western Edenside and Adjoining Areas, and the Drumlins of Edenside and the Solway Basin", Quarterly Journal of the Geological Society of London, Vol. 87, pp. 281-359.

Holmes, C.D., 1941, "Till Fabric", Bulletin of the Geological Society of America, Vol. 52, pp. 1299-1354.

Hoppe, G., 1951, "Drumlins i Nordostra Norrbotten", Geografiska Annaler, Vol. 33, pp. 157-165.

Hoppe, G. and V. Schytt, 1953, "Some Observations on Fluted Moraine Surfaces", Geografiska Annaler, Vol. 35, pp. 105-115.

Johansson, C.E., 1963, "Orientations of Pebbles in Running Water", Geografiska Annaler, Vol. 45, pp. 85-112.

Kamb, B., 1964, "Glacier Geophysics", Science, Vol. 146, pp. 353-365.

Kamb, B. and E. LaChapelle, 1964, "Direct Observation of the Mechanism of Glacier Sliding Over Bedrock", Journal of Glaciology, Vol. 5, pp. 159-172.

Krumbein, W.C. and F.J. Pettijohn, 1938, Manual of Sedimentary Petrography, New York, Appleton-Century-Crofts, Inc., 549 pp.

Kupsch, W.O., 1955, "Drumlins with Jointed Boulders near Dollard, Saskatchewan", Bulletin of the Geological Society of America, Vol. 66-2, pp. 327-338.

Lemke, R.W., 1958, "Narrow Linear Drumlins near Velva, North Dakota", American Journal of Science, Vol. 256, pp. 270-284.

Lichti-Federovich, S., 1970, "The Pollen Stratigraphy of a Section of Late-Pleistocene Lake Sediment from Central Alberta", Canadian Journal of Earth Science, Vol. 7, pp. 938-945.

Lliboutry, L., 1968, "General Theory of Subglacial Cavitation and Sliding of Temperate Glaciers", Journal of Glaciology, Vol. 7, pp. 21-58.

McCrossan, H.J. and R.P. Glaister, eds., 1964, Geological History of Western Canada, Calgary, Alberta, The Alberta Society of Petroleum Geologists, 232 pp.

McPherson, H.J. and J.S. Gardner, 1969, "The Development of Glacial Landforms in the Vicinity of the Saskatchewan Glacier", Canadian Alpine Journal, Vol. 52, pp. 90-96.

Nye, J.F., 1951, "The Flow of Glaciers and Ice-sheets as a Problem in Plasticity", Proceedings of the Royal Society, A, Vol. 207, pp. 554-572.

Ostry, R.C. and R.E. Deane, 1963, "Microfabric Analysis of Till", Geological Society of America Bulletin, Vol. 74, pp. 165-168.

Paterson, W.S.B., 1969, The Physics of Glaciers, Oxford, Pergamon Press, 250 pp.

Pearson, E.S. and H.O. Hartley, 1954, Biometrika Tables for Statisticians, Volume 1, London, The Cambridge University Press, 238 pp..

Personal Communication with Keith D. Hage, Professor, Department of Geography, University of Alberta, June, 1971.

Personal Communication with Will Harrison, Assistant Professor, Department of Atmospheric Sciences, University of Washington, Seattle, Washington, March, 1971.

Personal Communication with John A. Westgate, Associate Professor, Department of Geology, University of Alberta, June, 1971.

Prest, V.K., 1970, "Retreat of Wisconsin and Recent Ice in North America", Geological Survey of Canada, Map 1257-A, Scale, 1:5,000,000.

Preston, F.W., 1966, "Two-dimensional Power Spectra for Classification of Landforms", Kansas State Geological Survey, Computer Contribution 7, pp. 64-69.

Ramsden, J. and J.A. Westgate, 1971, "Evidence for Reorientation of a Till Fabric in the Edmonton Area", in Symposium on Till, R.P. Goldthwait, ed., Ohio State University Press, (In press).

Ray, L.L., 1935, "Some Minor Features of Valley Glaciers and Valley Glaciation", Journal of Geology, Vol. 43, pp. 297-322.

Rayner, J.N., 1971, An Introduction to Spectral Analysis, London, Pion Press, 221 pp.

Reed, B., C.J. Galvin and J.P. Miller, 1962, "Some Aspects of Drumlin Geometry", American Journal of Science, Vol. 260, pp. 200-210.

Sitler, R.F., 1968, "Glacial Till in Oriented Thin Section", Twenty-third International Geological Congress, Vol. 8, pp. 283-295.

Smalley, I.J. and D.J. Unwin, 1968, "The Formation and Shape of Drumlins and their Distribution and Orientation in Drumlin Fields", Journal of Glaciology, Vol. 7, pp. 377-390.

Smith, H.T.U., 1948, "Giant Glacial Grooves in Northwest Canada", American Journal of Science, Vol. 246, pp. 503-514.

Steinmetz, R., 1962, "Analysis of Vectorial Data", Journal of Sedimentary Petrology, Vol. 32, pp. 801-812.

Tarr, R.S., 1894, "The Origin of Drumlins", American Geologist, Vol. 13, pp. 393-407.

Taylor, G.I., 1923, "Stability of Viscous Liquid Contained Between Two Rotating Cylinders", Philosophical Transactions of the Royal Society of London, Series A, 223, pp. 289-343.

Taylor, P.S., 1960, "Some Pleistocene Lakes of Northern Alberta and Adjacent Areas (Revised)", Journal of the Alberta Society of Petroleum Geologists, Vol. 8, pp. 167-178.

Wardlaw, N.C., M.R. Stauffer and M. Hoque, 1969, "Striations, Giant Grooves and Superposed Drag Folds, Interlake Area, Manitoba", Canadian Journal of Earth Science, Vol. 6, pp. 577-593.

Watson, G.S., 1956, "Analysis of Dispersion on a Sphere", Monthly Notices of the Royal Astronomical Society, Geophysical Supplement, Vol. 7, pp. 153-159.

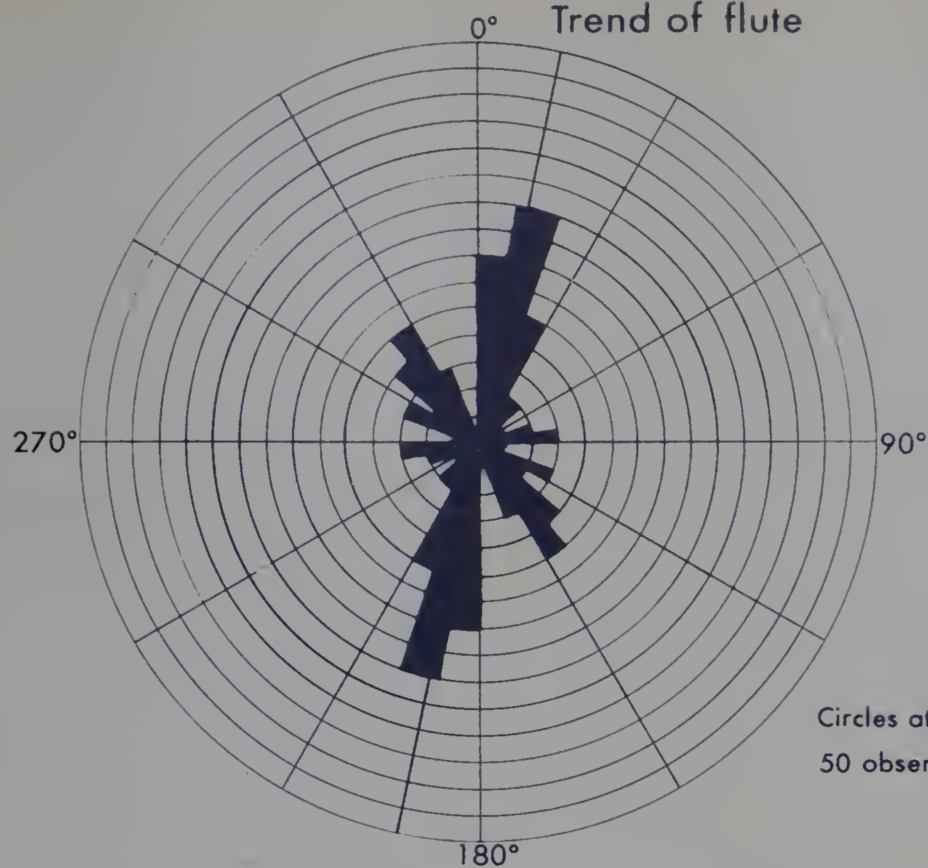
Weertman, J., 1957, "On the Sliding of Glaciers", Journal of Glaciology, Vol. 3, pp. 33-38.

Weertman, J., 1964, "The Theory of Glacial Sliding", Journal of Glaciology, Vol. 5, pp. 287-303.

Wright, H.E., 1957, "Stone Orientation on the Wadena Drumlin Field, Minnesota", Geografiska Annaler, Vol. 39, pp. 19-31.

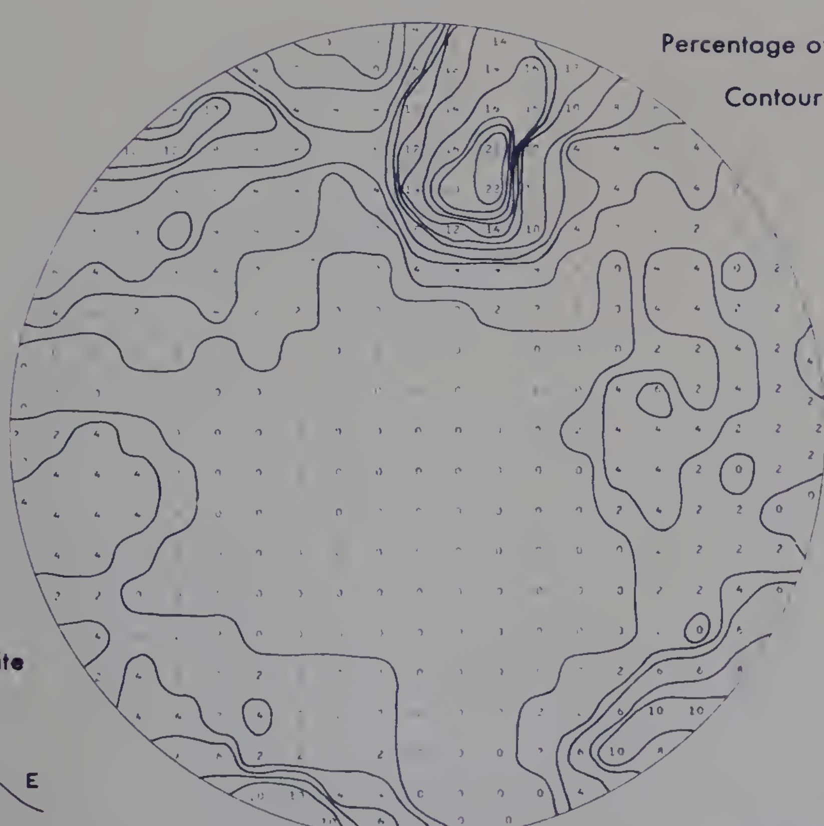
APPENDIX

Flute 1 Fabric A



Circles at one pebble frequency

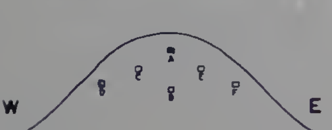
50 observations



Percentage of points per 3% area

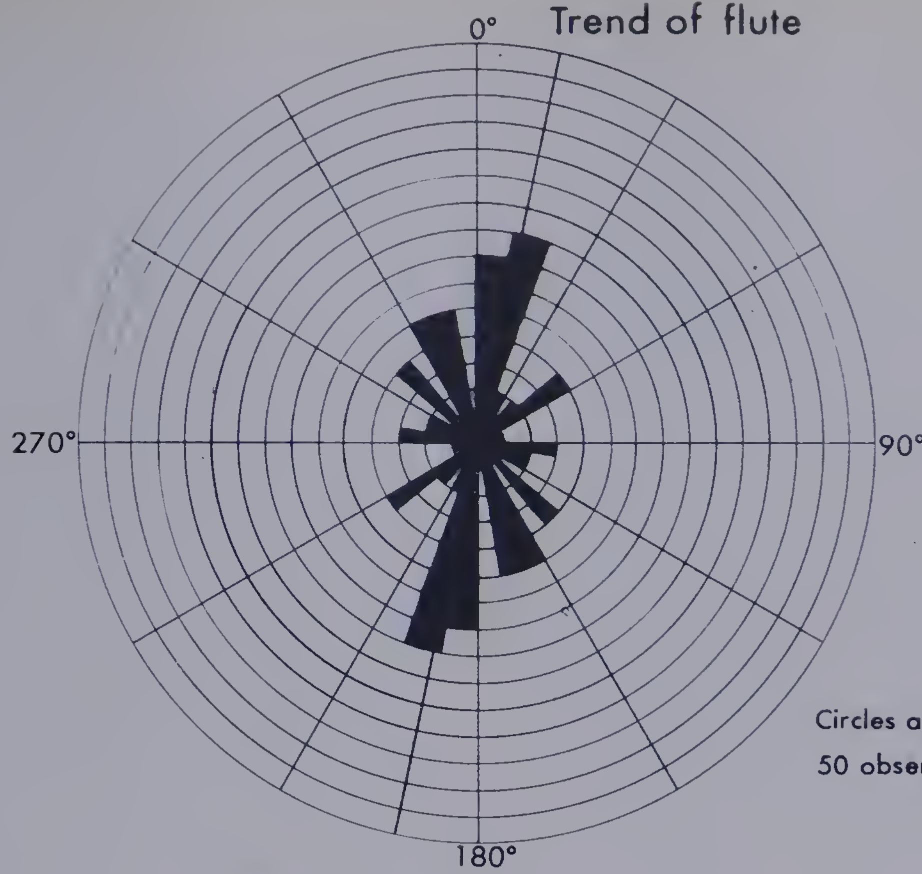
Contour interval 2%

Location of fabric site

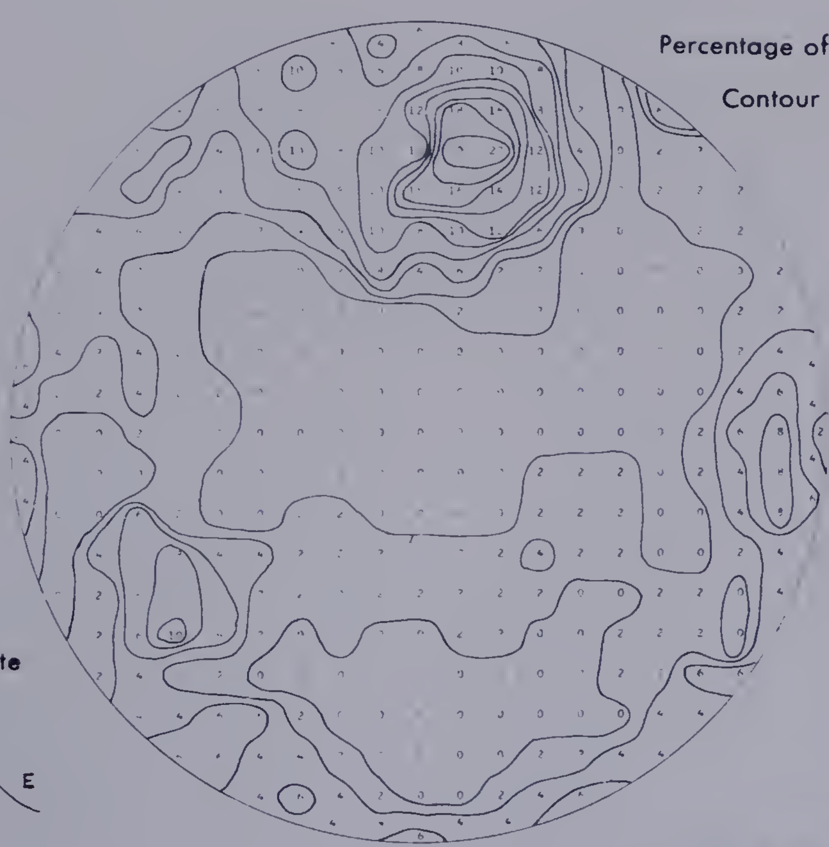


Confidence limit (5%) 20°

Flute I Fabric B

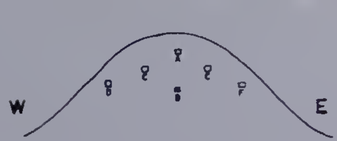


Circles at one pebble frequency
50 observations



Percentage of points per 3% area
Contour interval 2%

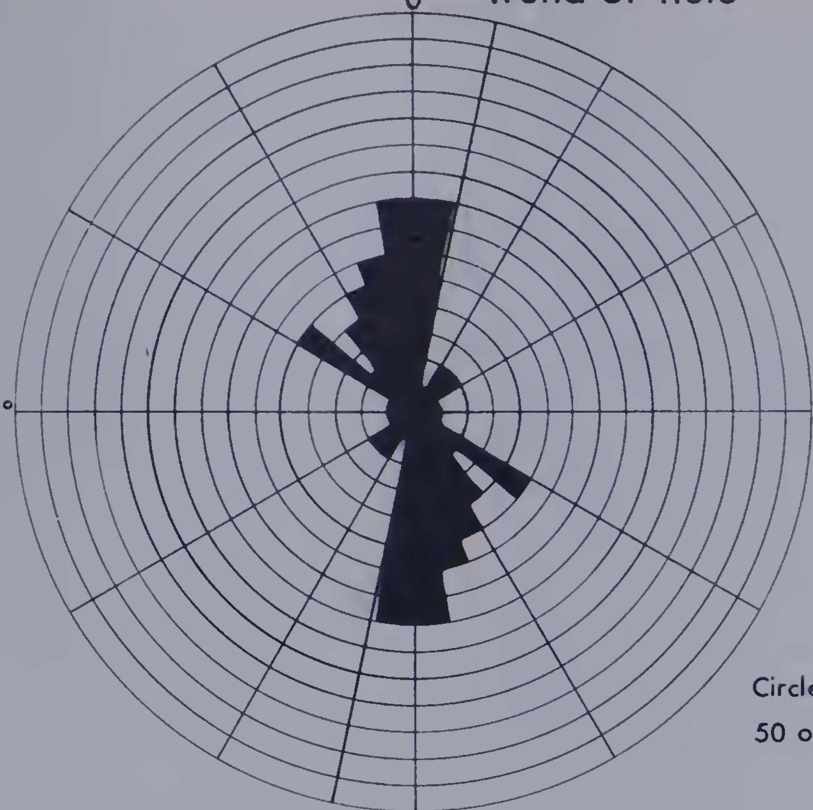
Location of fabric site



Confidence limit (5%) 22°

Flute I Fabric C

0° Trend of flute

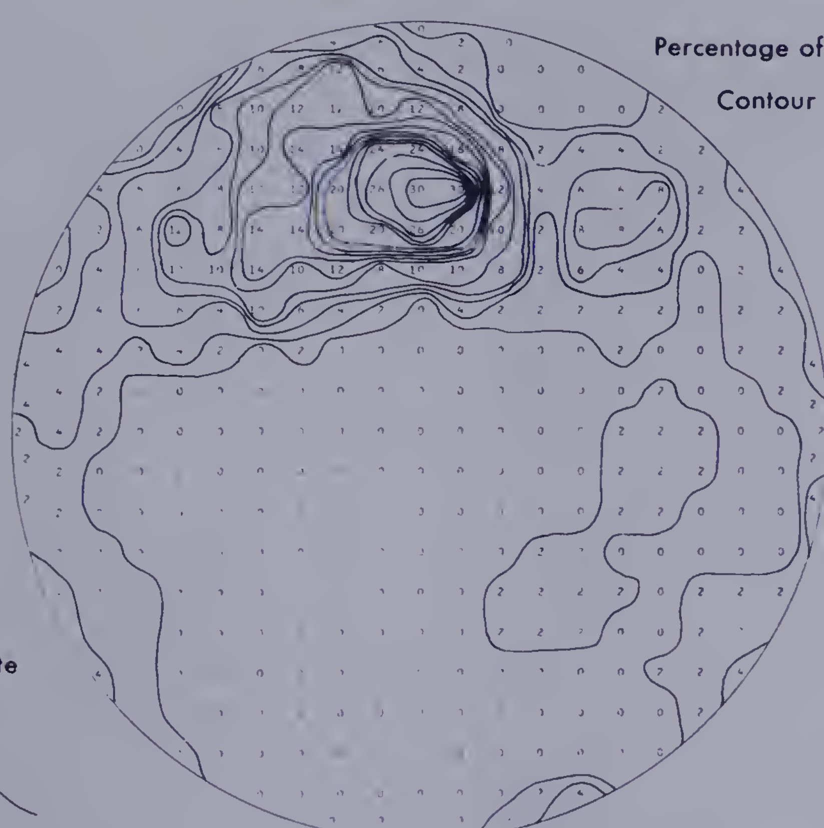


Circles at one pebble frequency

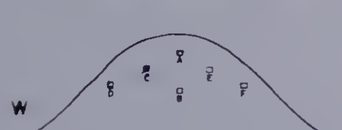
50 observations

Percentage of points per 3% area

Contour interval 2%

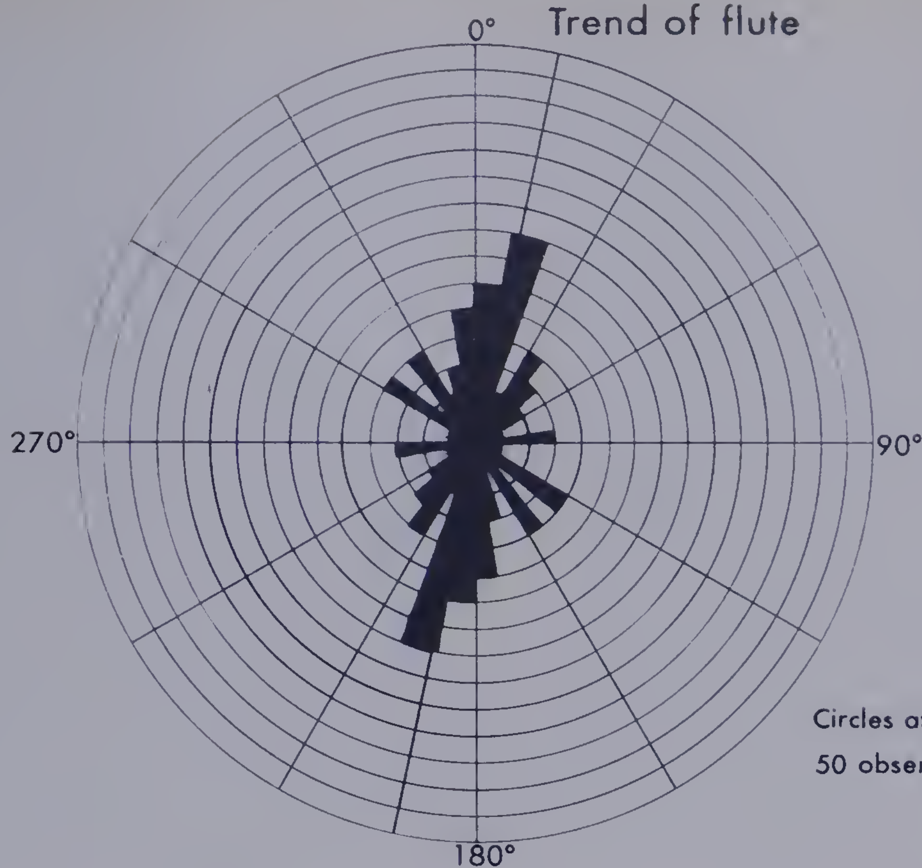


Location of fabric site



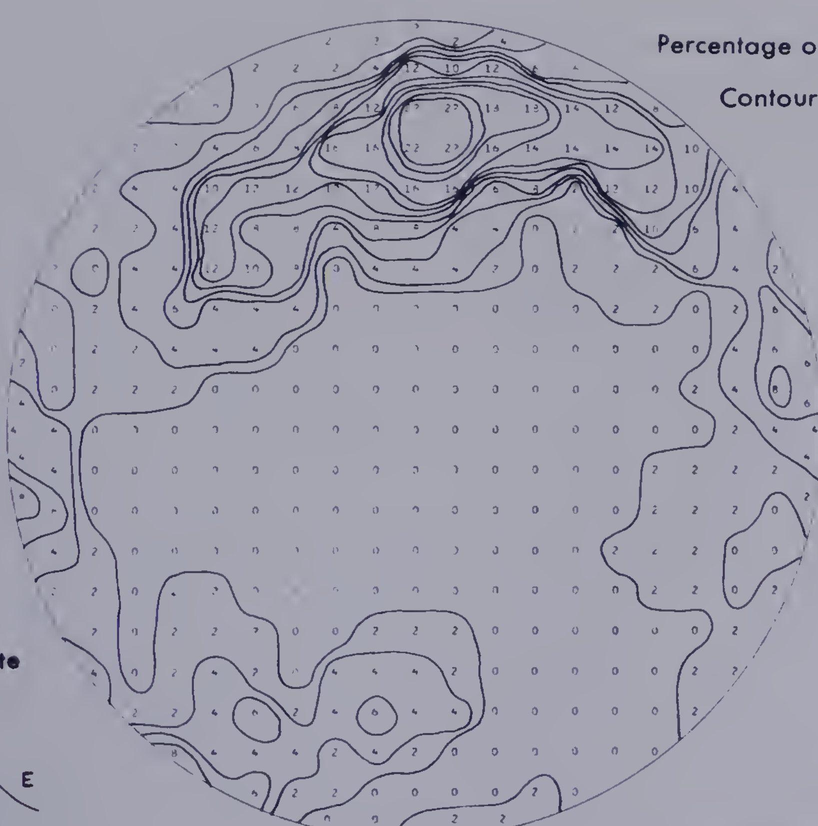
Confidence limit (5%) 11°

Flute I Fabric D



Circles at one pebble frequency

50 observations



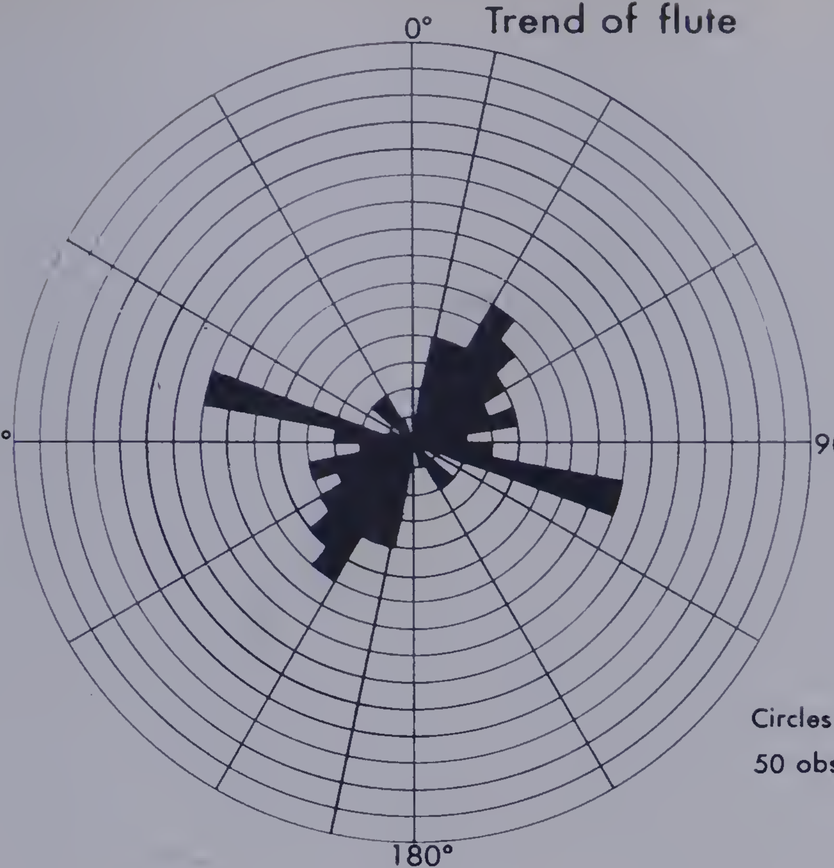
Percentage of points per 3% area

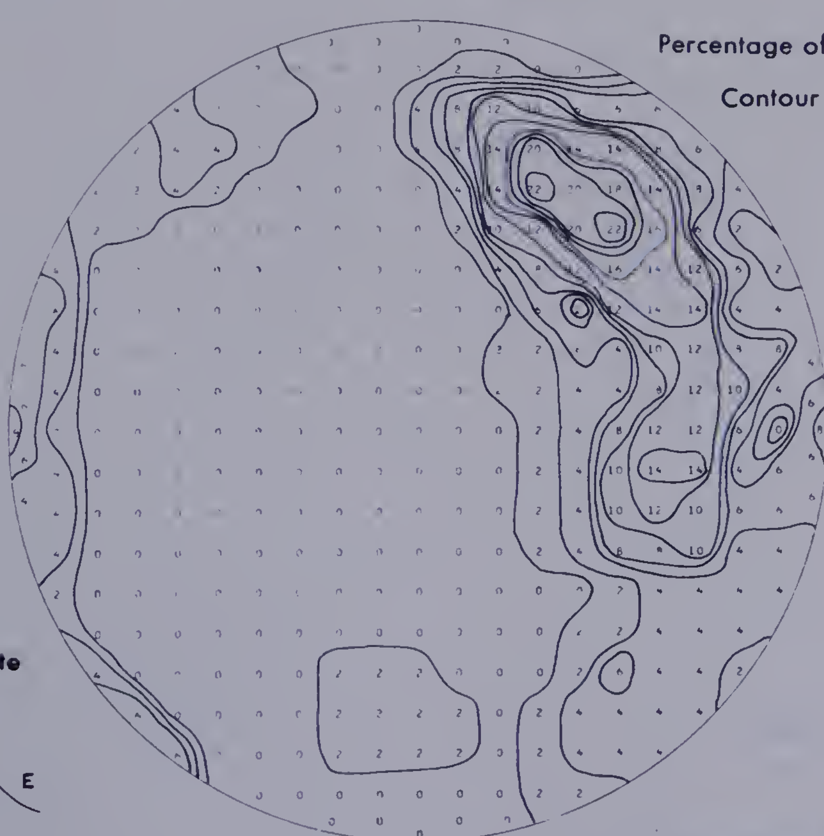
Contour interval 2%

Location of fabric site

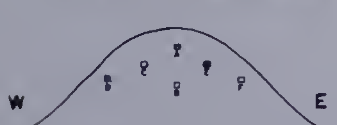
Confidence limit (5%) 16°

Flute I Fabric E



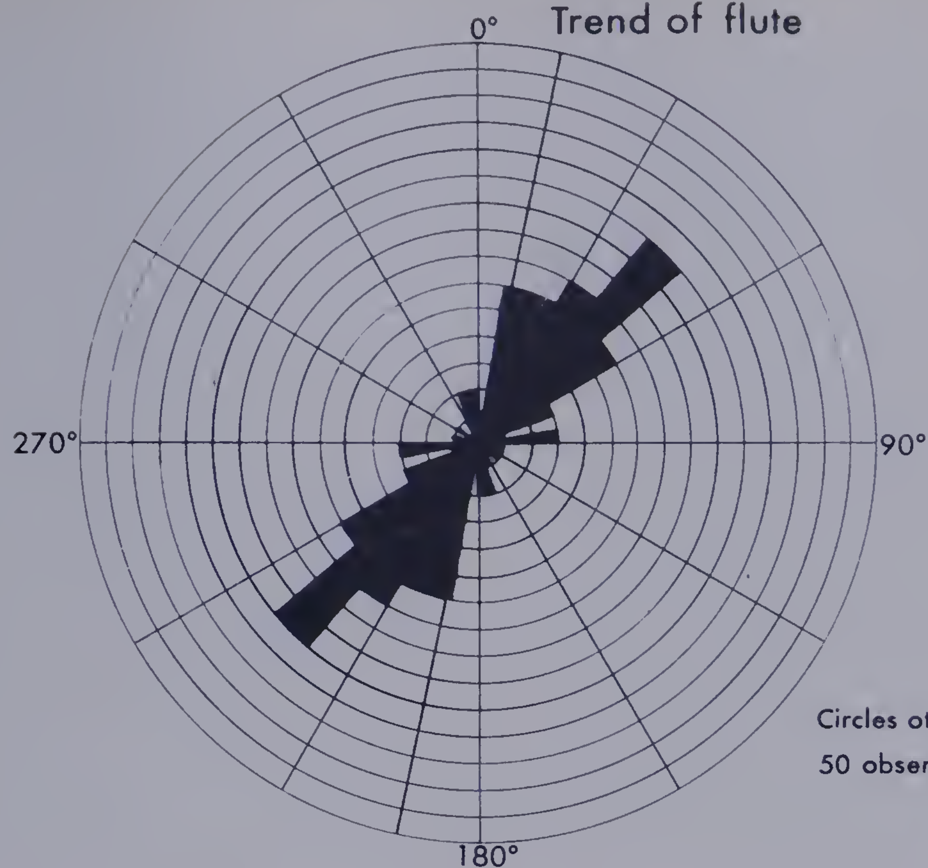


Location of fabric site

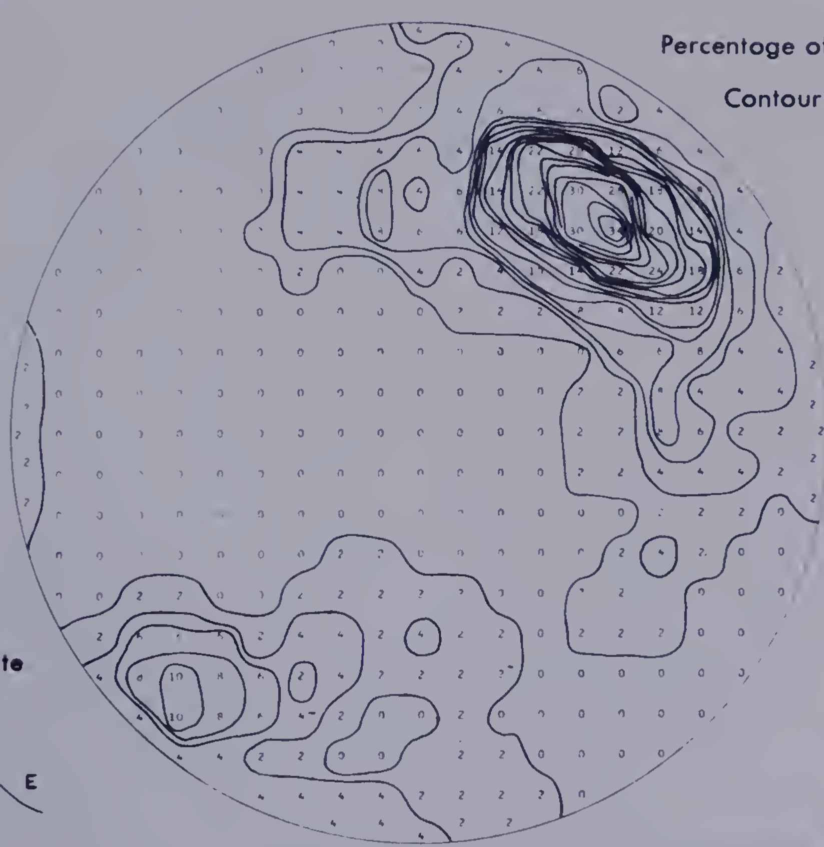


Confidence limit (5%) 12°

Flute I Fabric F

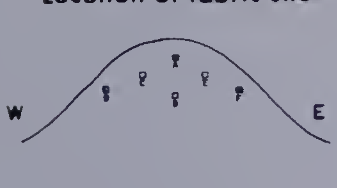


Circles at one pebble frequency
50 observations



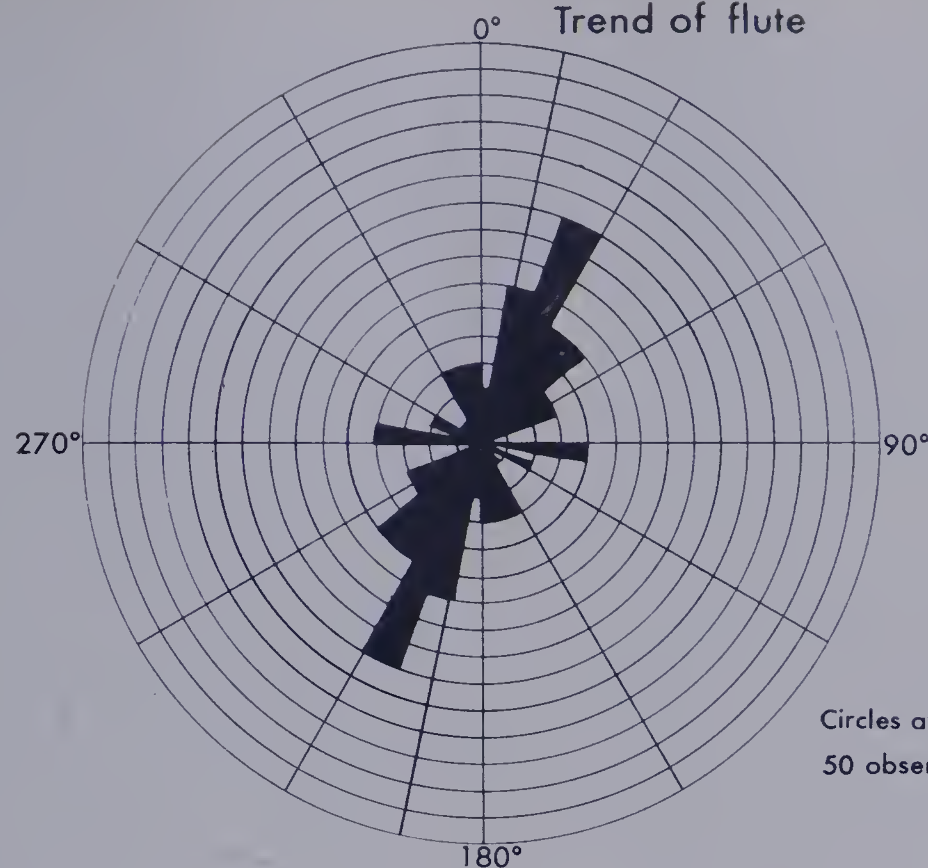
Percentage of points per 3% area
Contour interval 2%

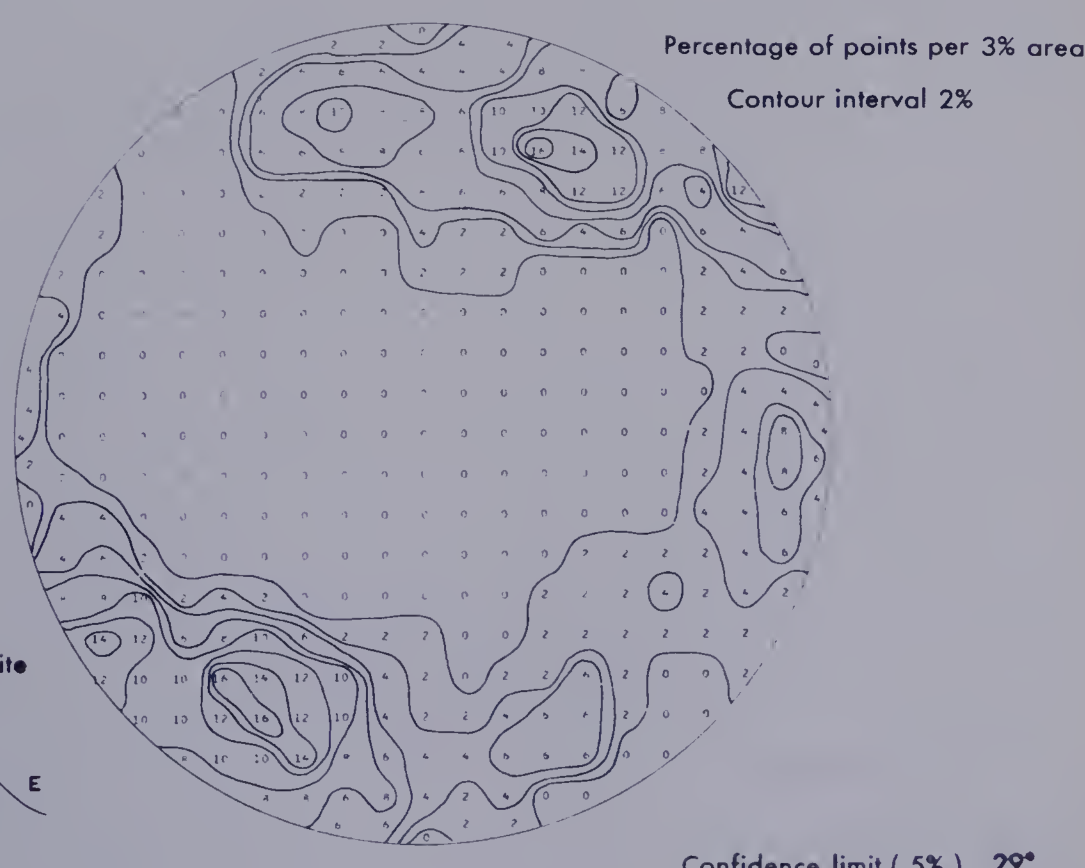
Location of fabric site



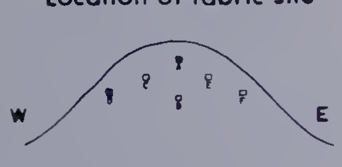
Confidence limit (5%) 15°

Flute 2 Fabric A

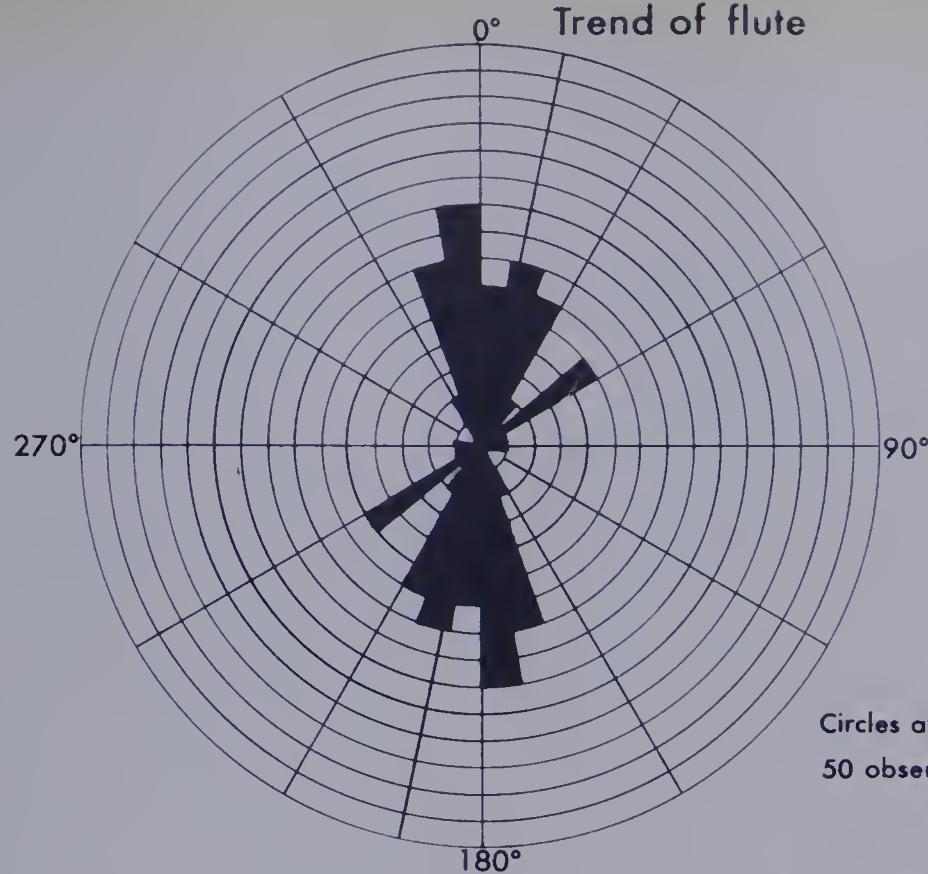




Location of fabric site

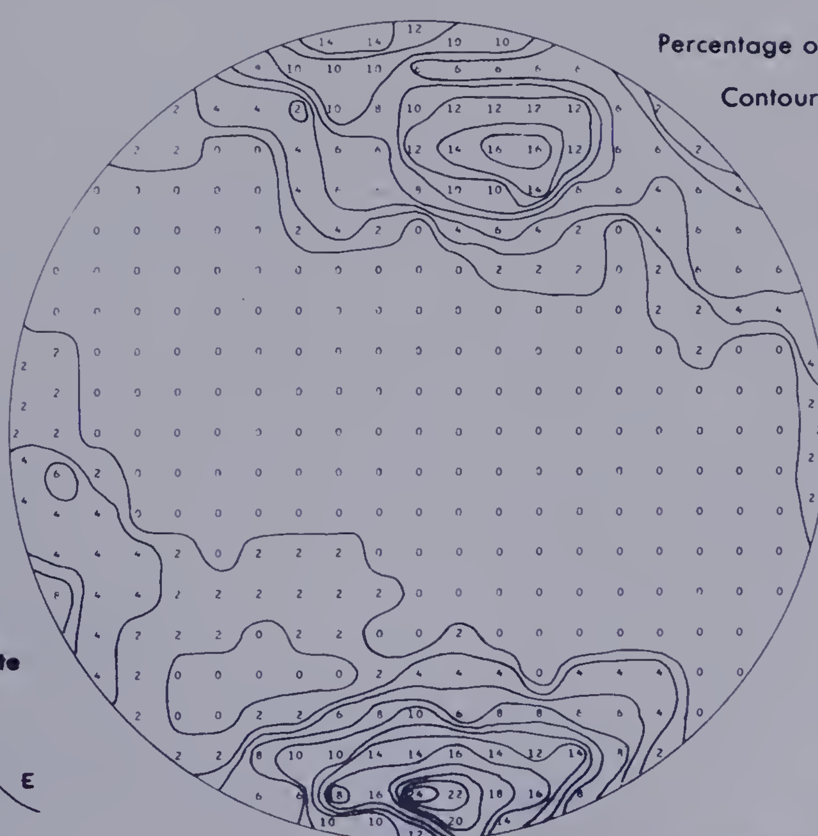


Flute 2 Fabric B

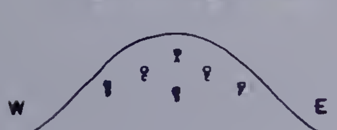


Circles at one pebble frequency
50 observations

Percentage of points per 3% area
Contour interval 2%

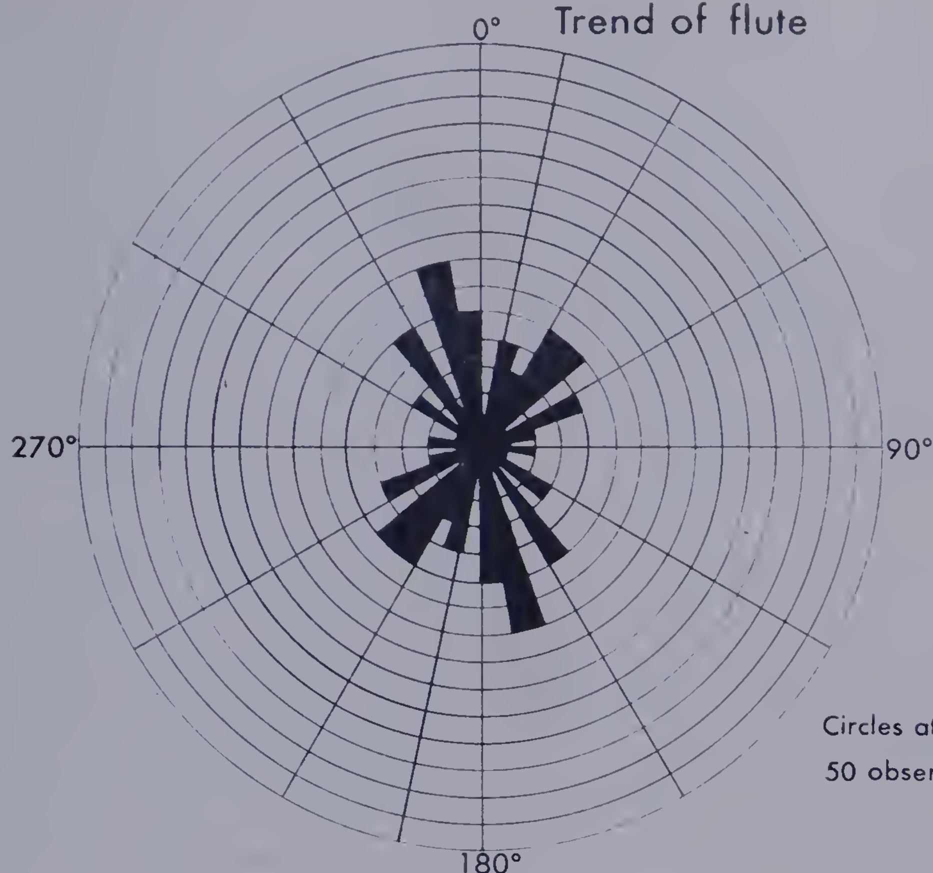


Location of fabric site



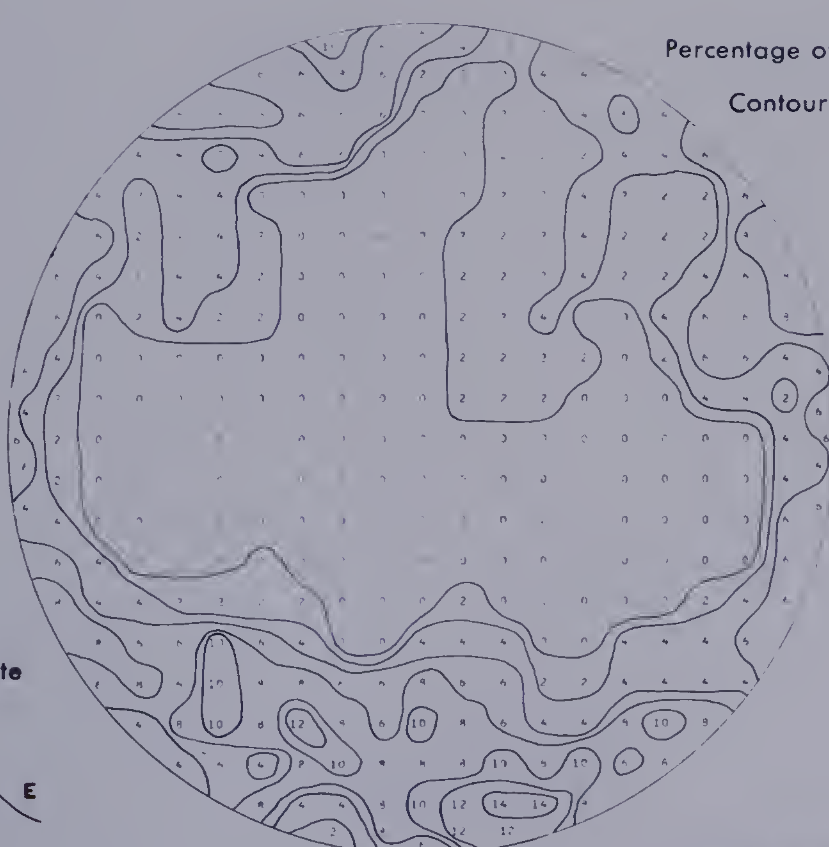
Confidence limit (5%) 31°

Flute 2 Fabric C

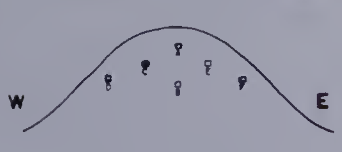


Circles at one pebble frequency
50 observations

Percentage of points per 3% area
Contour interval 2%



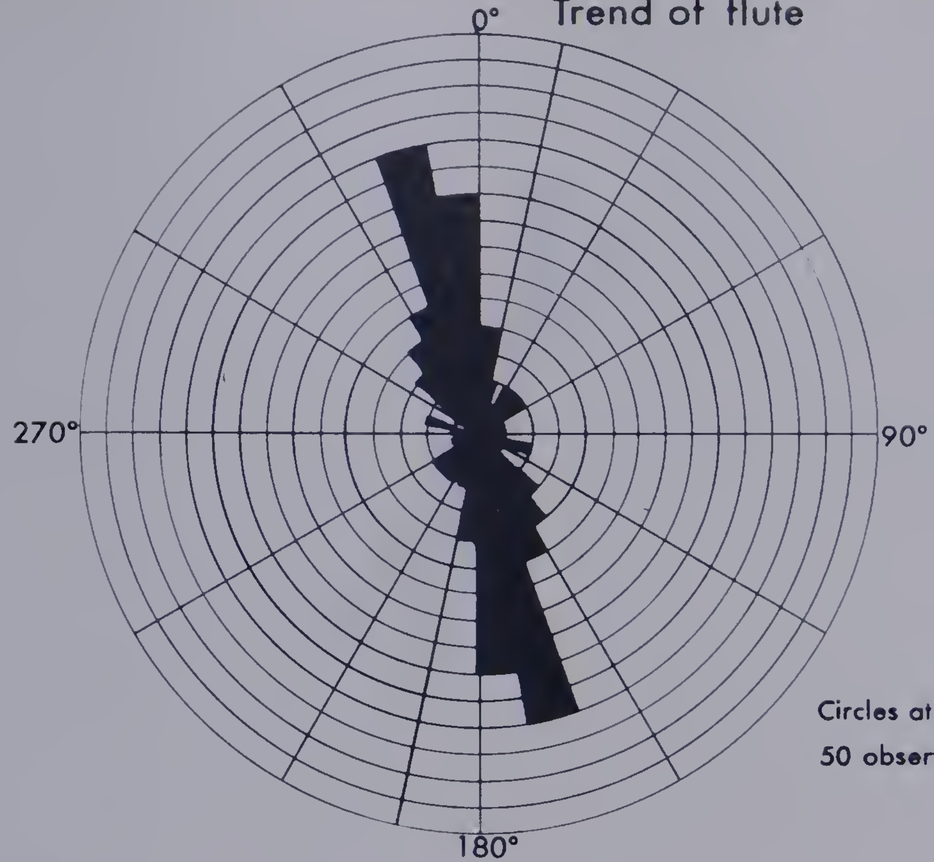
Location of fabric site



Confidence limit (5%) 25°

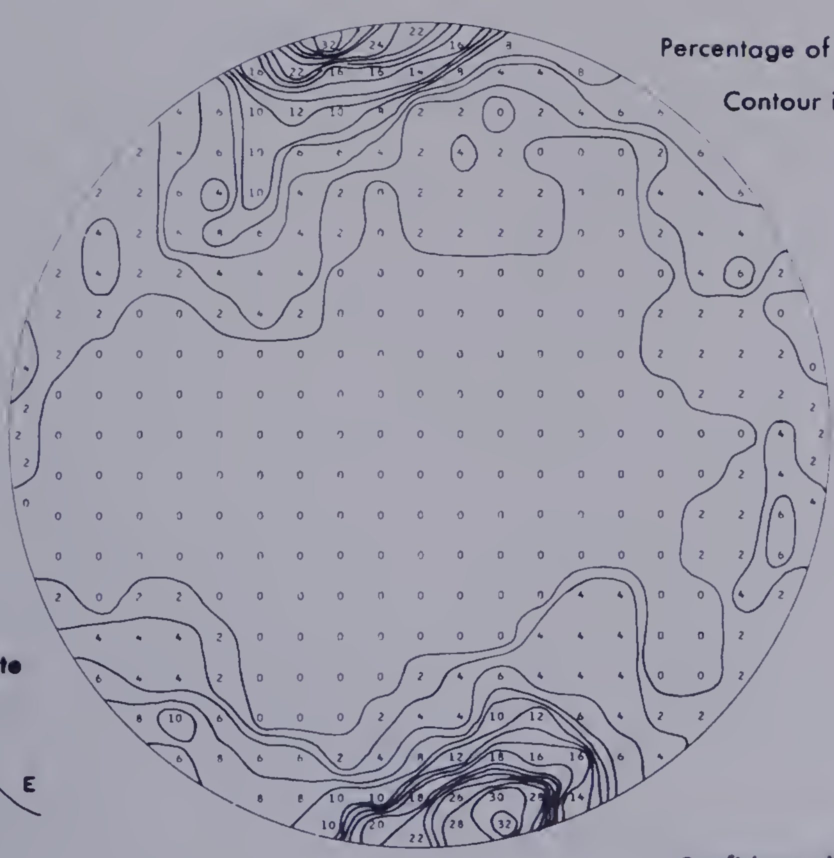
Flute 2 Fabric D

Trend of flute



Circles at one pebble frequency
50 observations

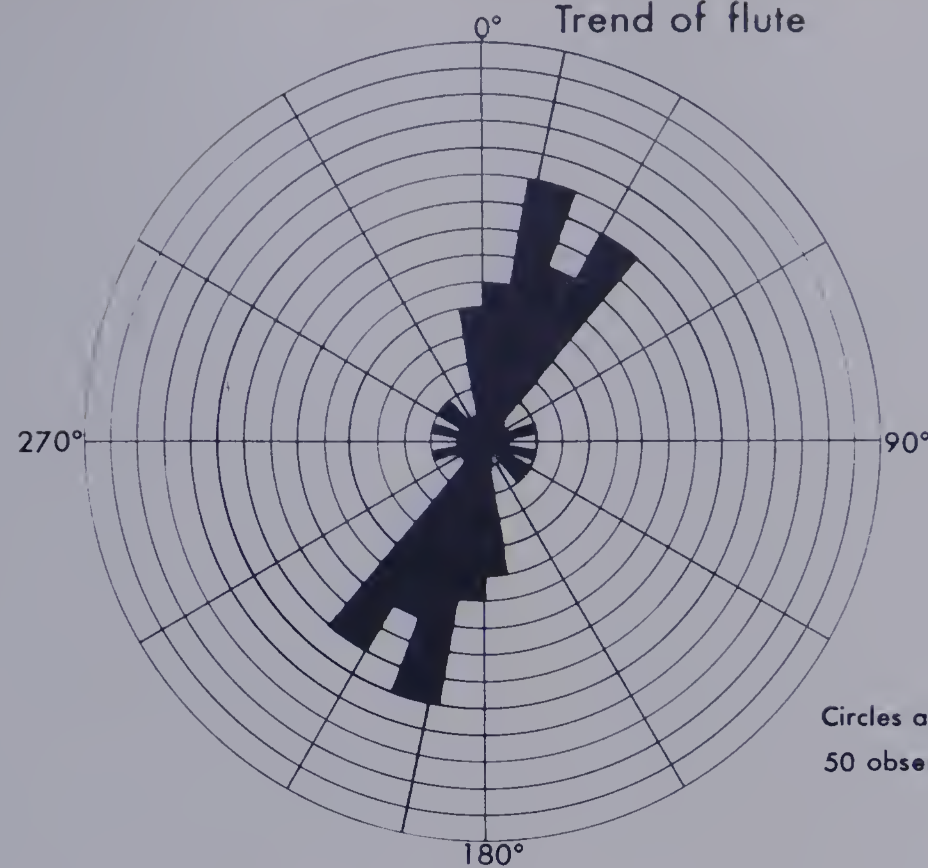
Percentage of points per 3% area
Contour interval 2%



Location of fabric site

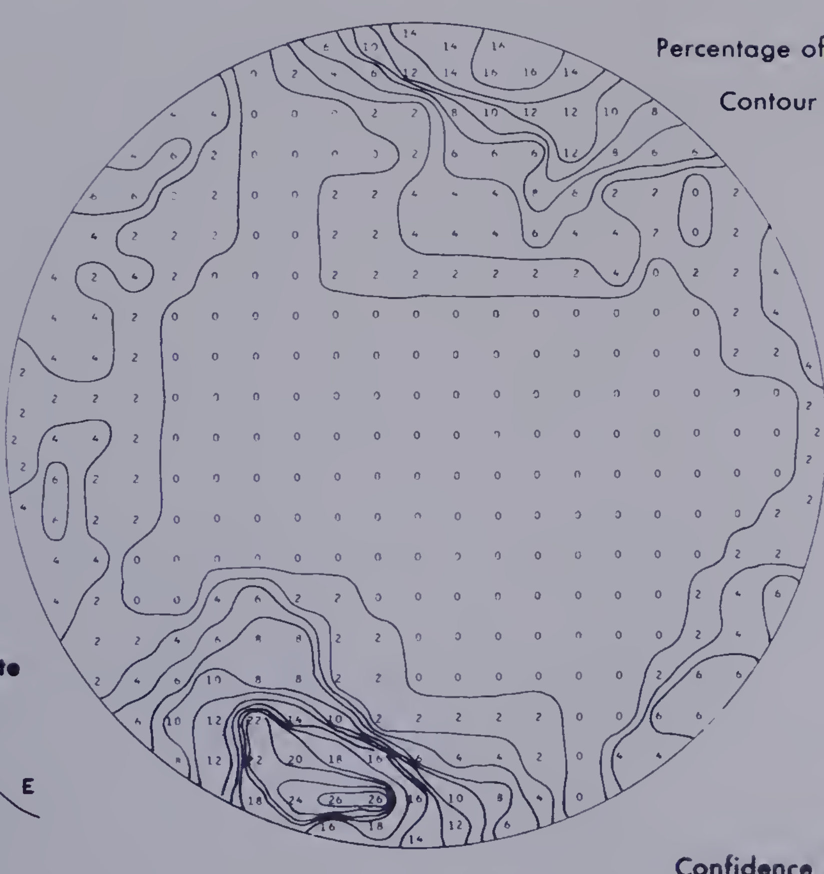
Confidence limit (5%) 32°

Flute 2 Fabric E

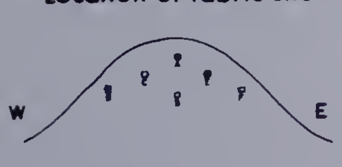


Circles at one pebble frequency
50 observations

Percentage of points per 3% area
Contour interval 2%

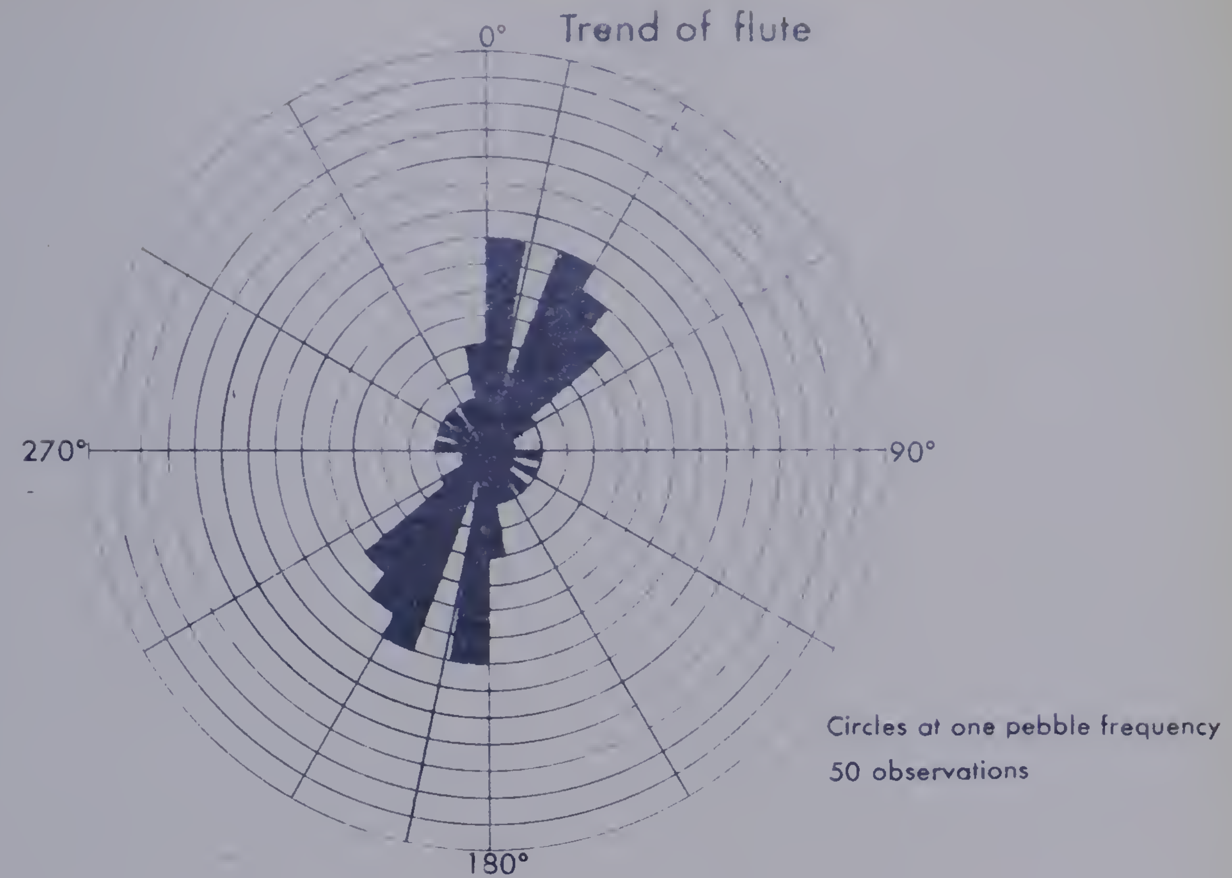


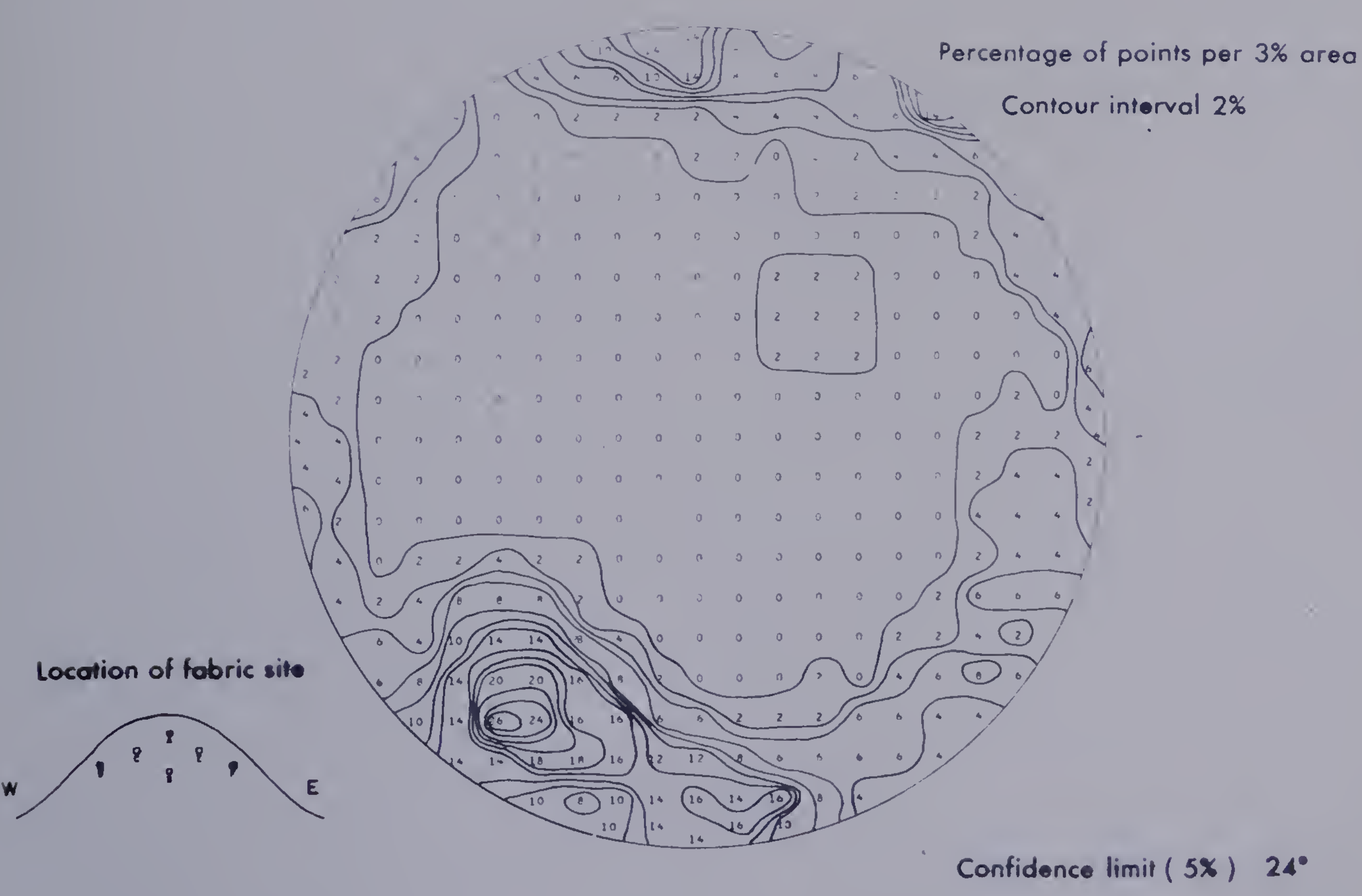
Location of fabric site



Confidence limit (5%) 33°

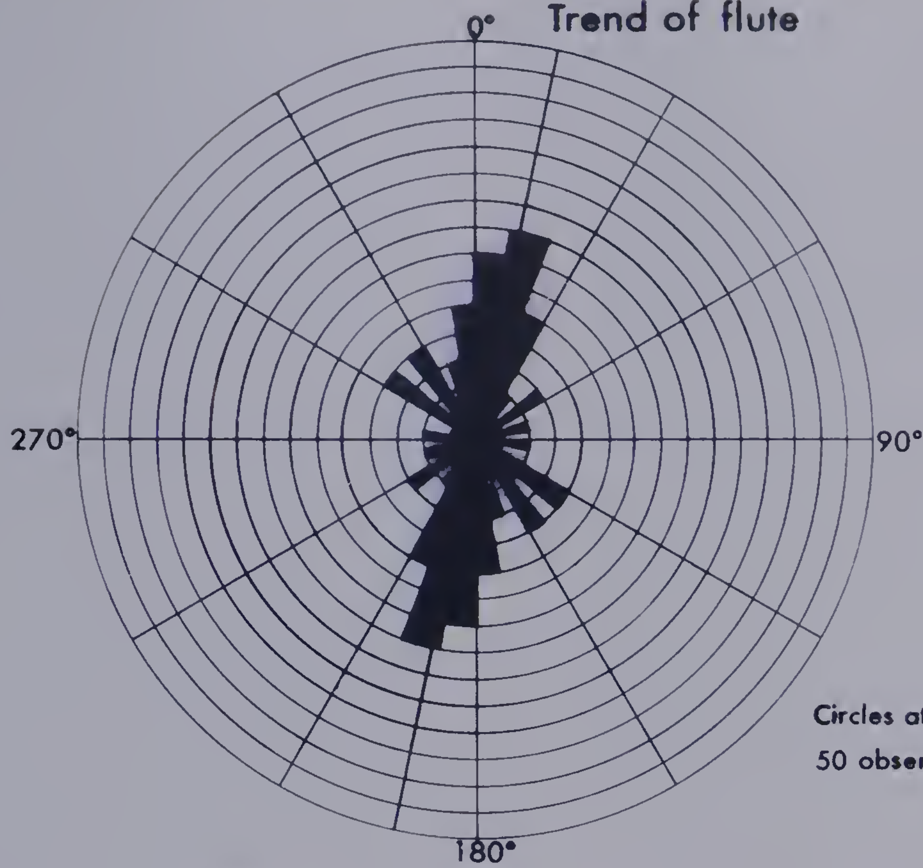
Flute 2 Fabric F





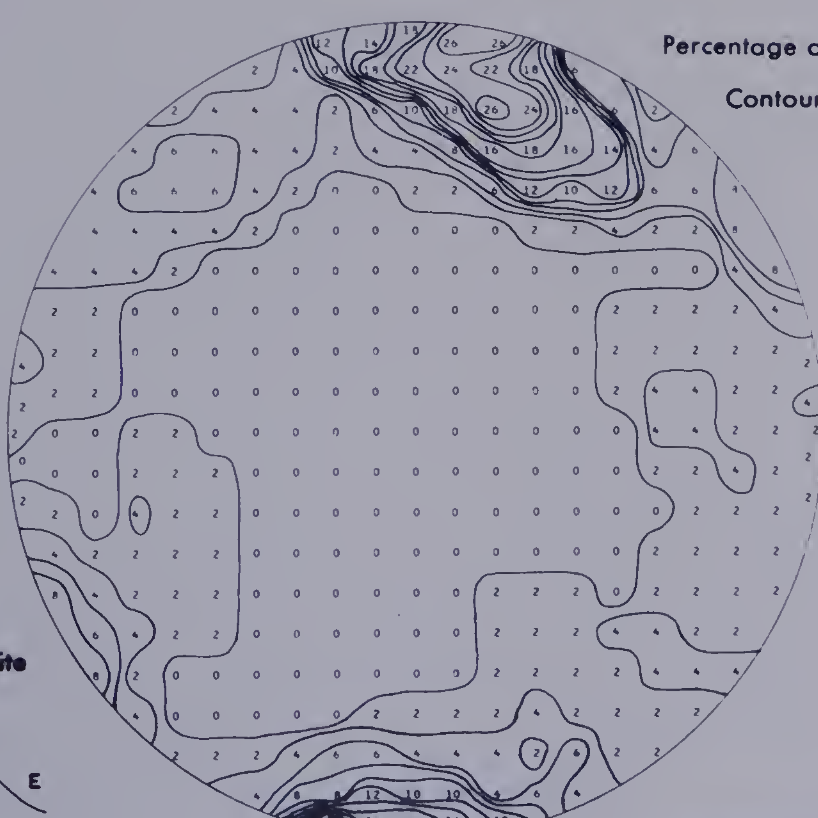
Flute 3 Fabric A

Trend of flute

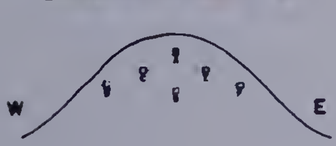


Circles at one pebble frequency
50 observations

Percentage of points per 3% area
Contour interval 2%

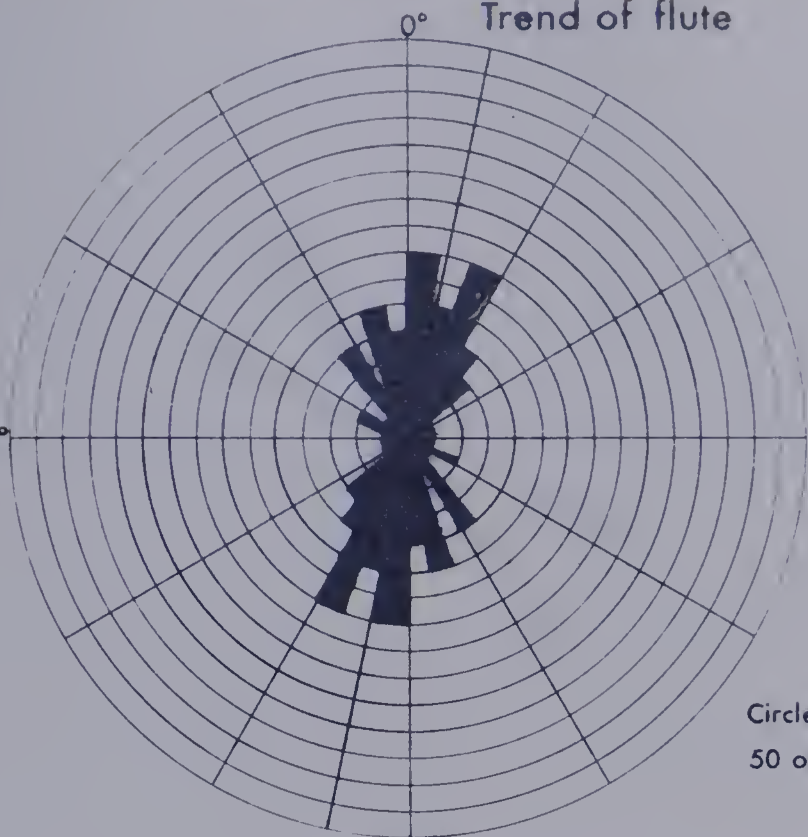


Location of fabric site

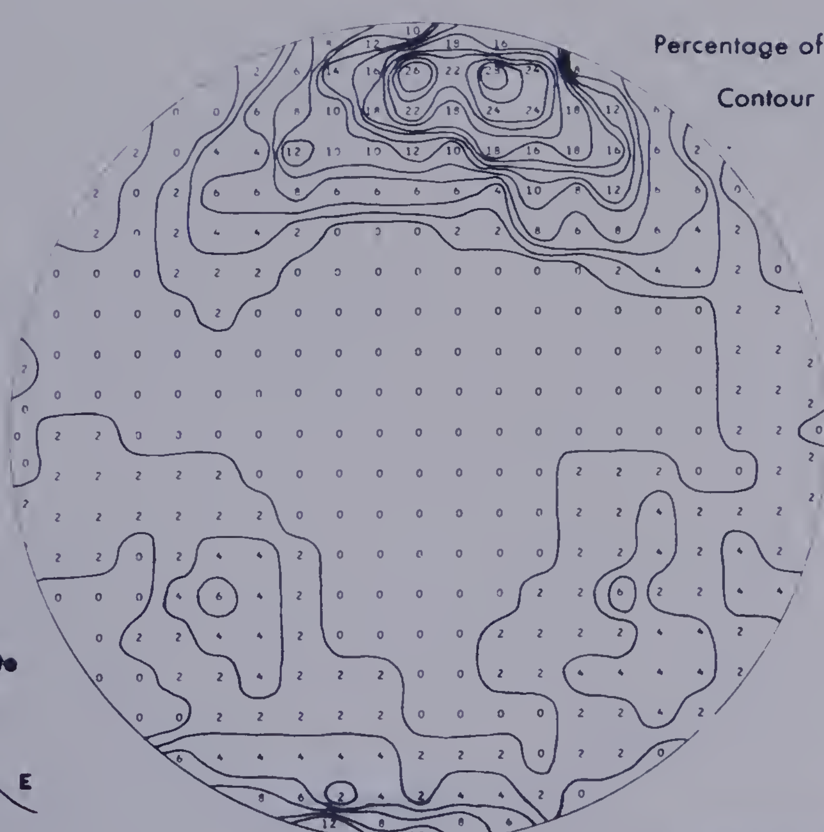


Confidence limit (5%) 25°

Flute 3 Fabric B

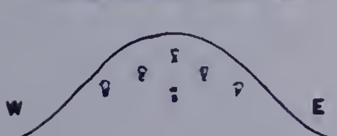


Circles at one pebble frequency
50 observations



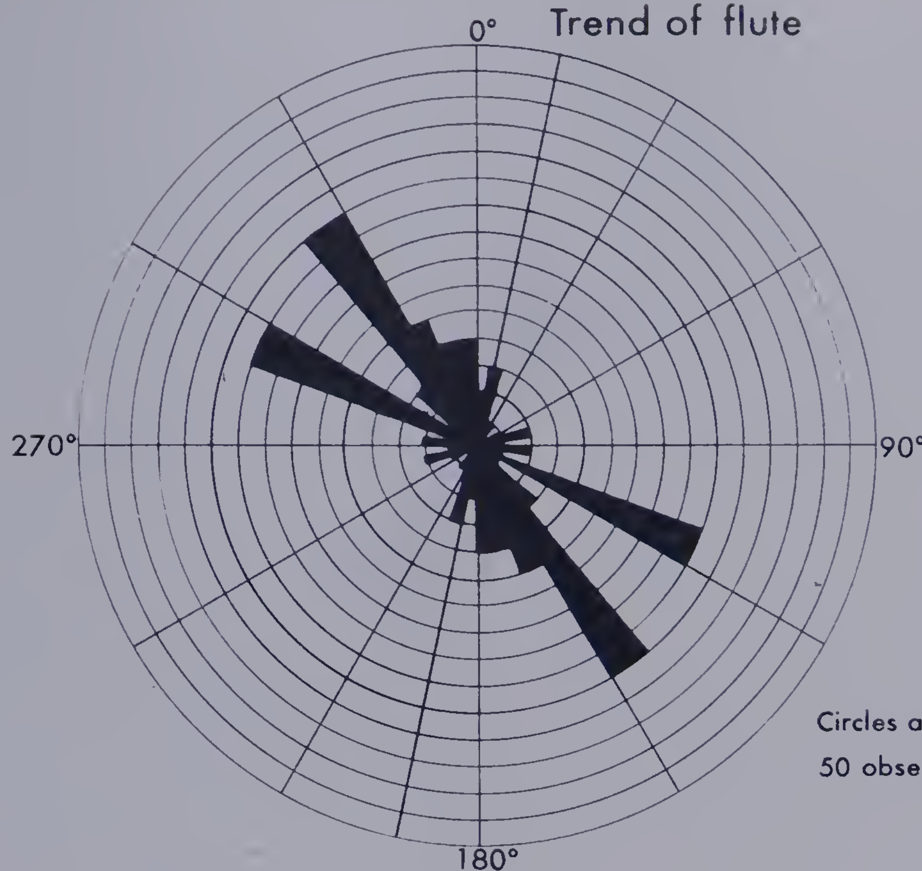
Percentage of points per 3% area
Contour interval 2%

Location of fabric site

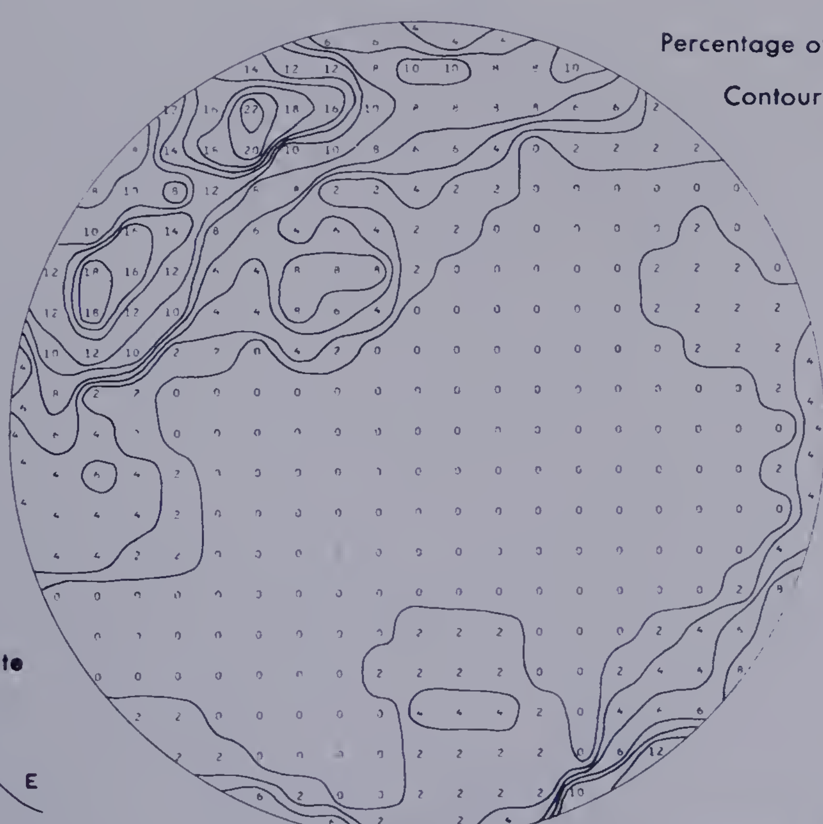


Confidence limit (5%) 17°

Flute 3 Fabric C

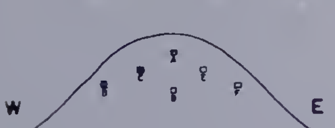


Circles at one pebble frequency
50 observations



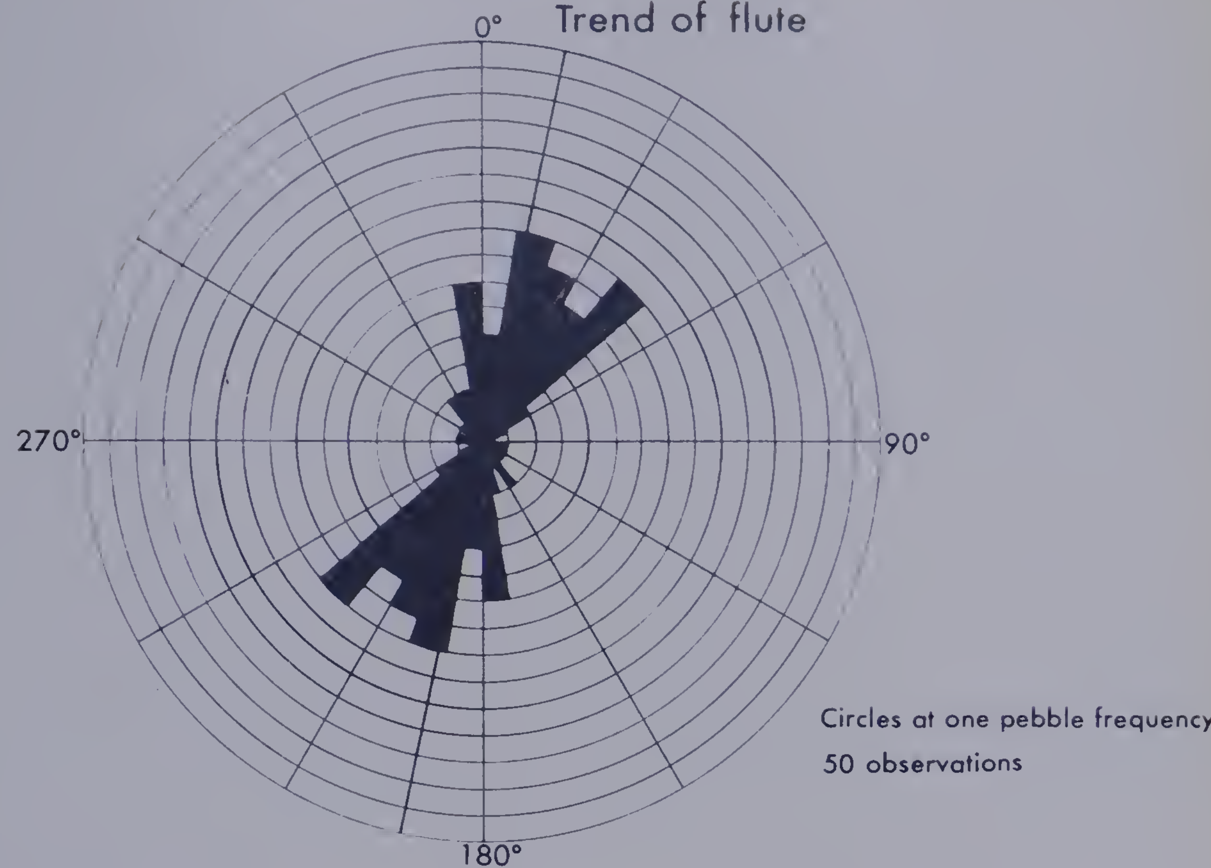
Percentage of points per 3% area
Contour interval 2%

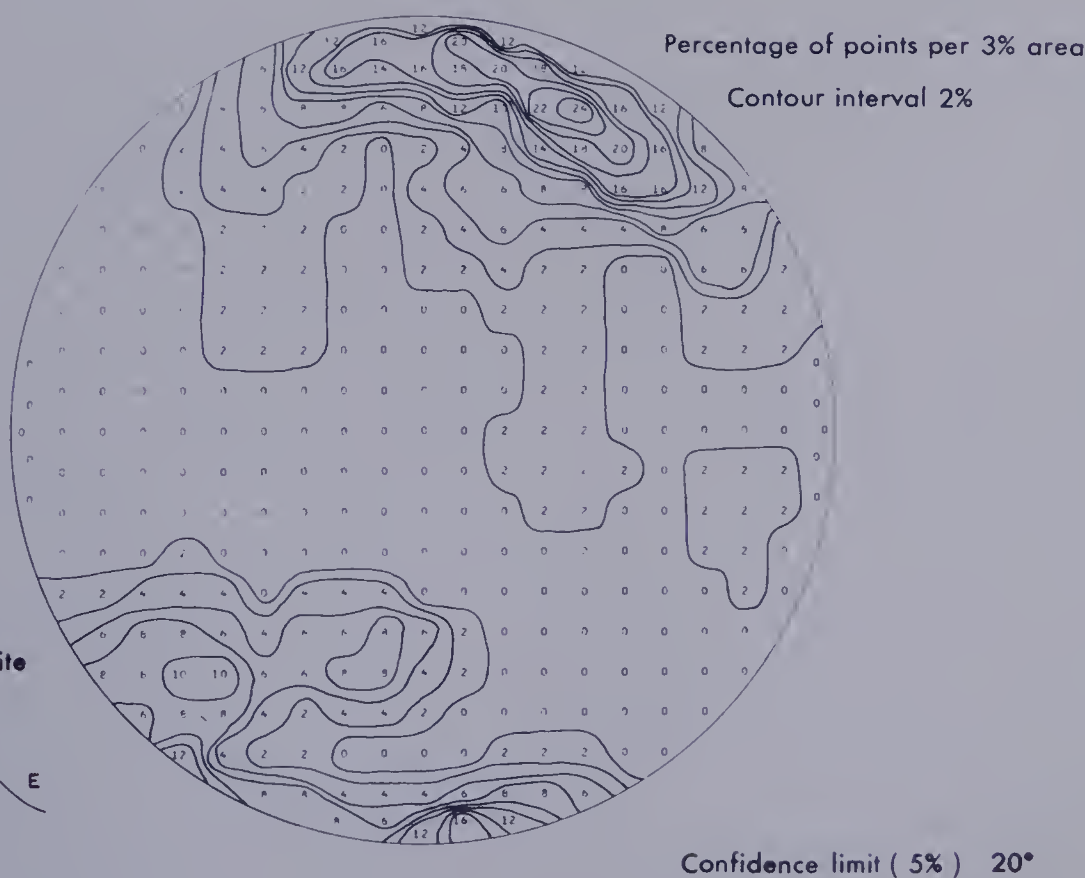
Location of fabric site

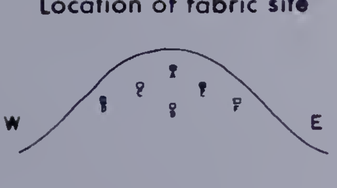


Confidence limit (5%) 14°

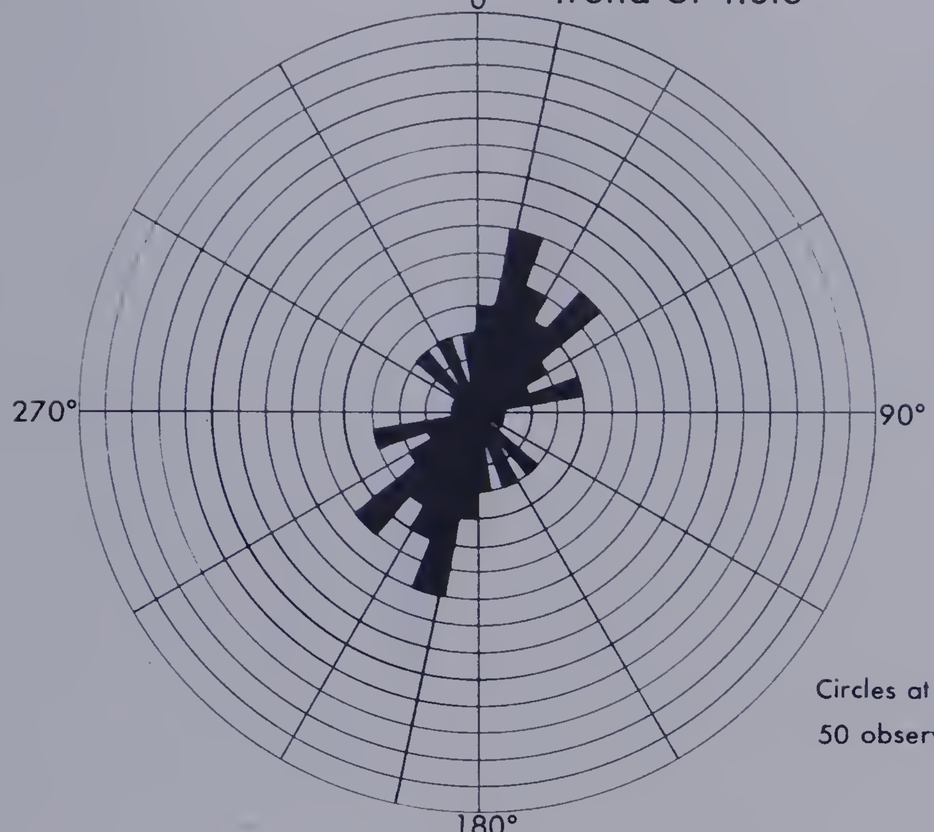
Flute 3 Fabric E



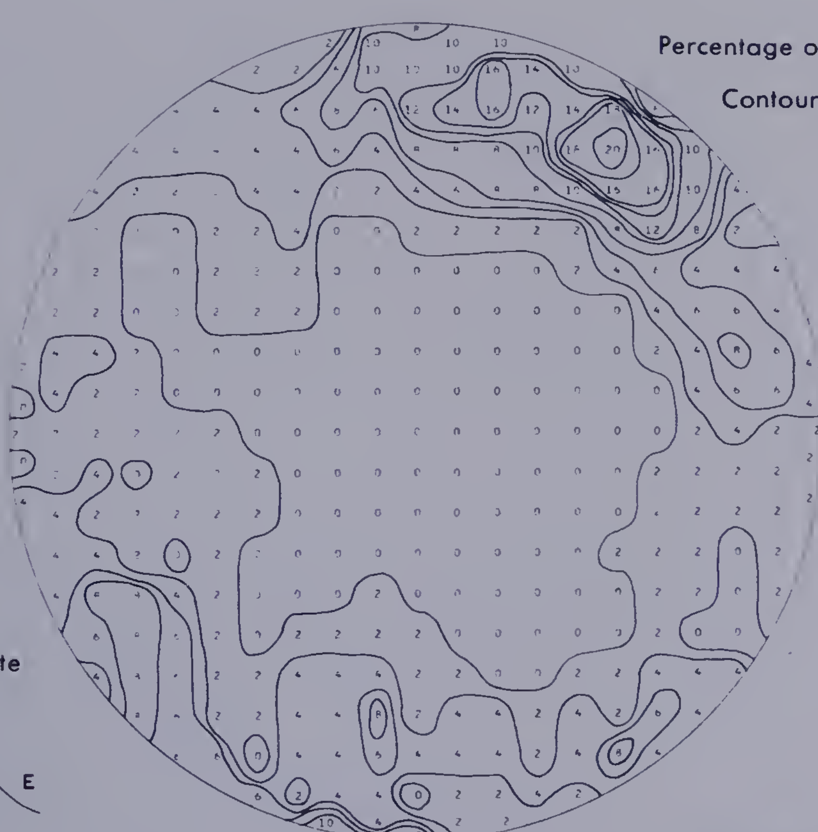




Flute 3 Fabric F

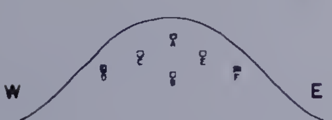


Circles at one pebble frequency
50 observations



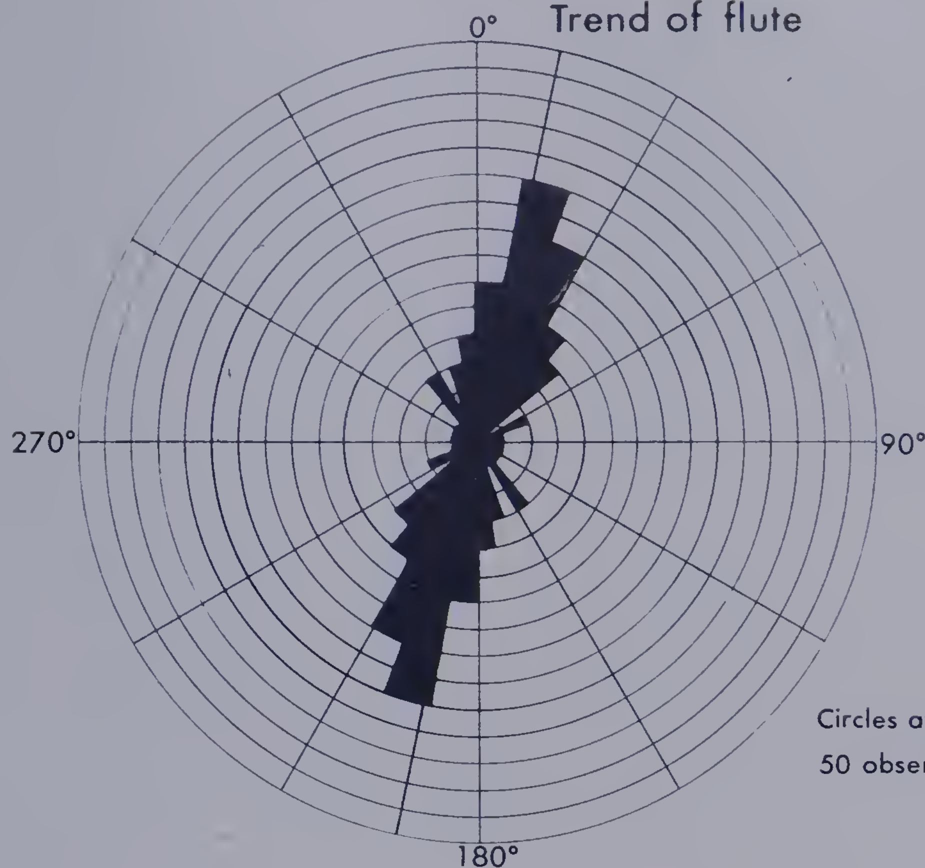
Percentage of points per 3% area
Contour interval 2%

Location of fabric site

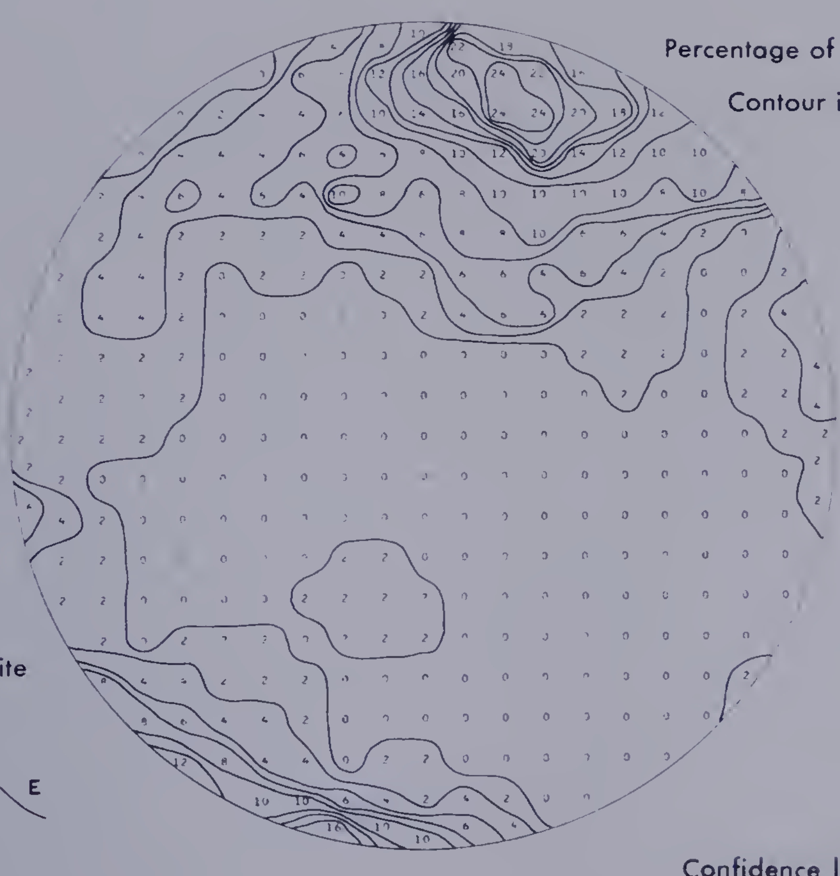


Confidence limit (5%) 23°

Flute 4 Fabric A



Circles at one pebble frequency
50 observations

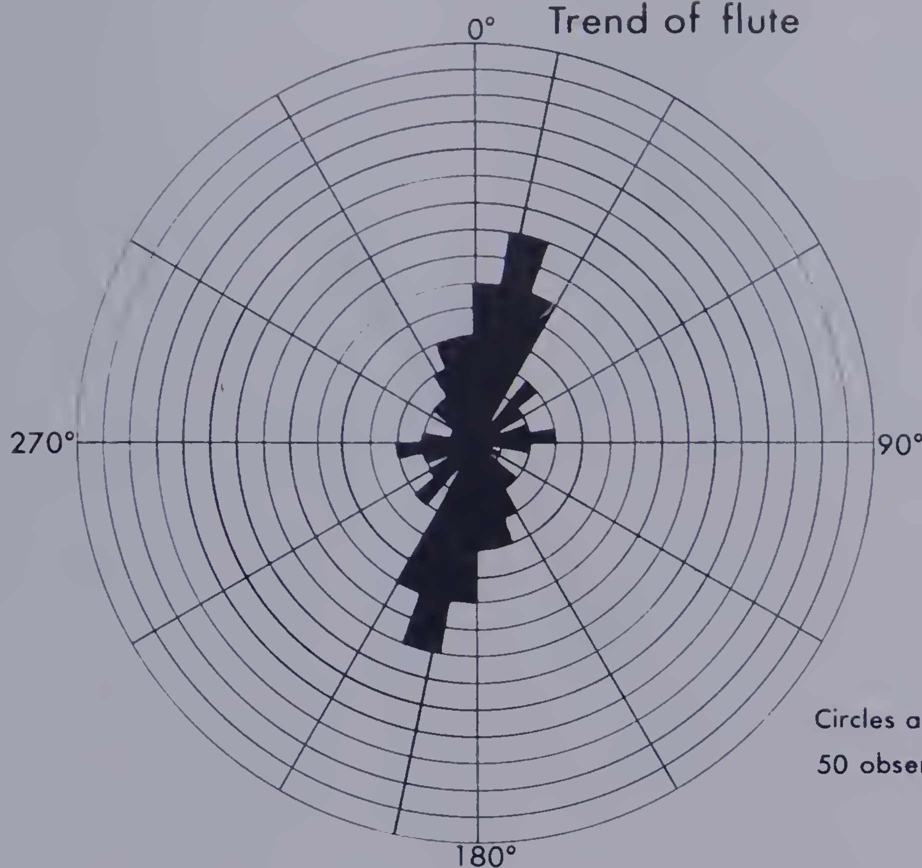


Percentage of points per 3% area
Contour interval 2%

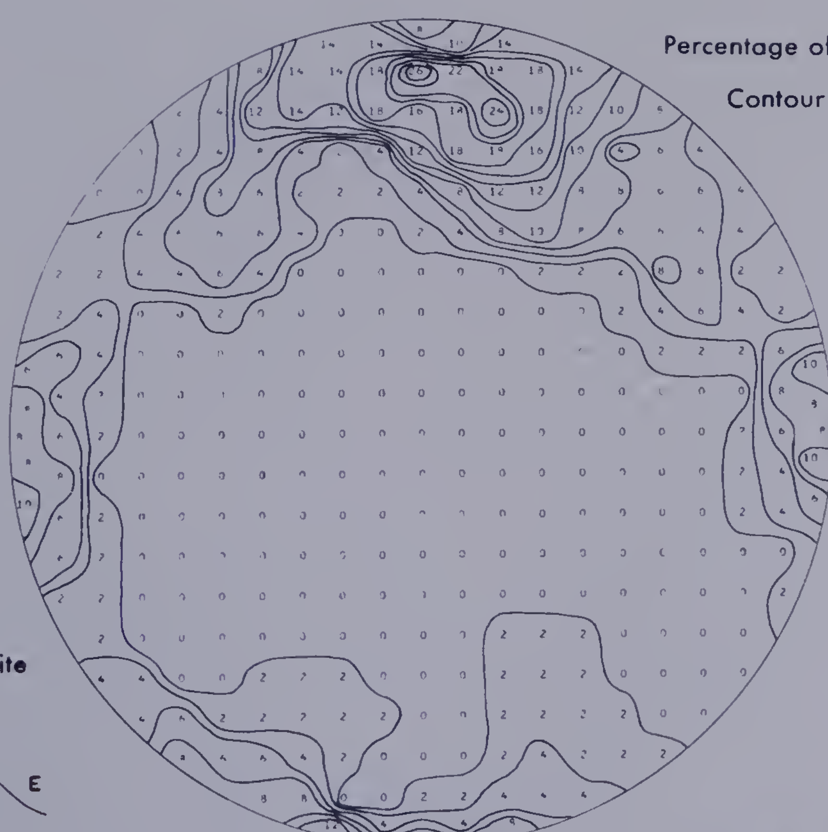
Location of fabric site

Confidence limit (5%) 15°

Flute 4 Fabric B

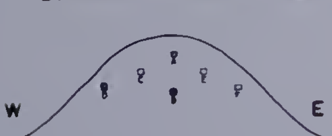


Circles at one pebble frequency
50 observations



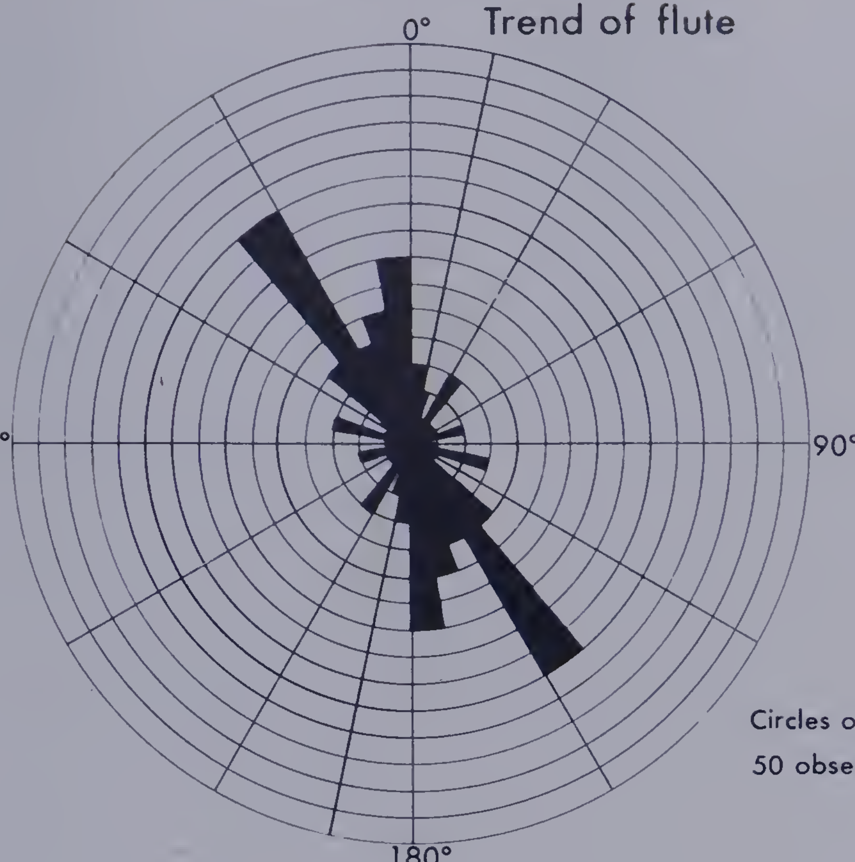
Percentage of points per 3% area
Contour interval 2%

Location of fabric site

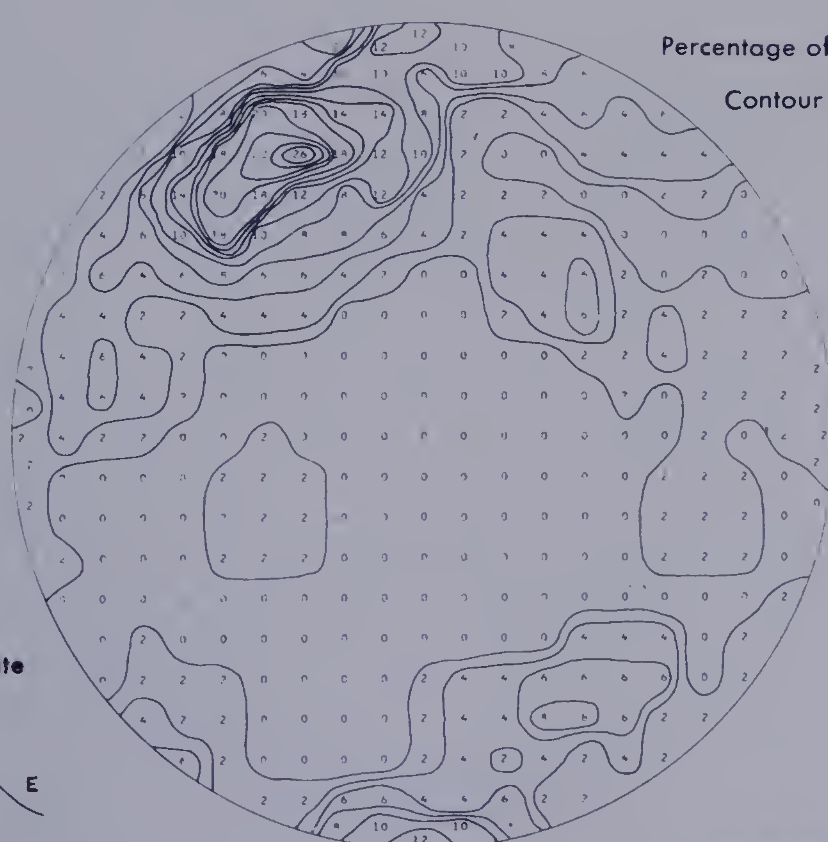


Confidence limit (5%) 19°

Flute 4 Fabric C



Circles of one pebble frequency
50 observations

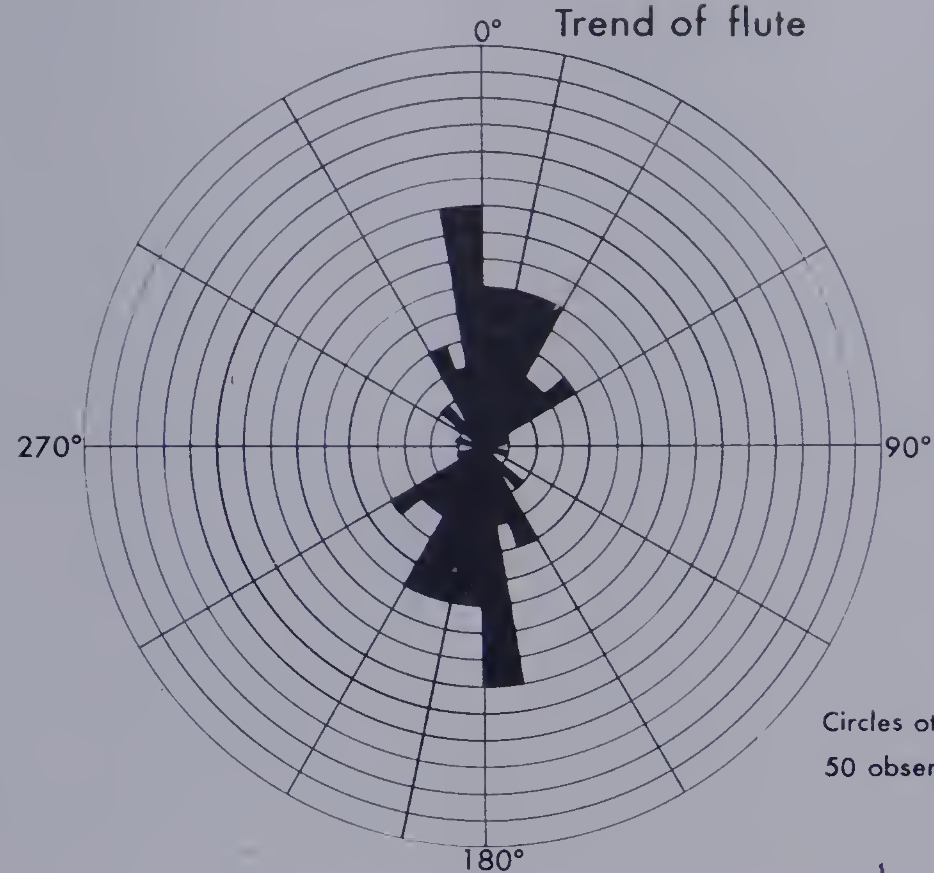


Percentage of points per 3% area
Contour interval 2%

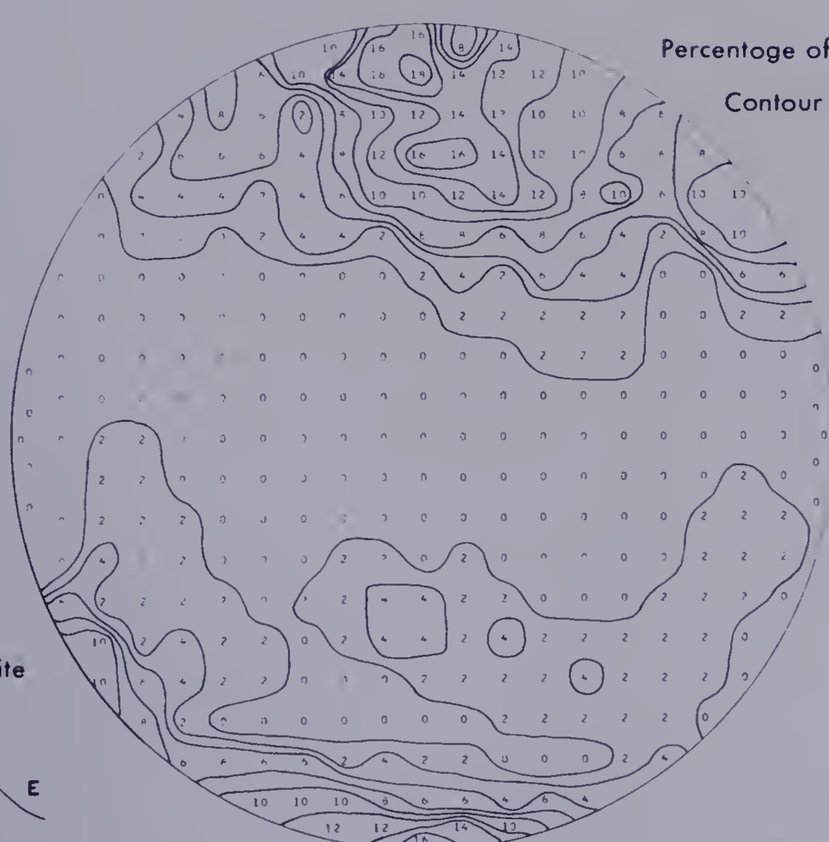
Location of fabric site

Confidence limit (5%) 19°

Flute 4 Fabric D

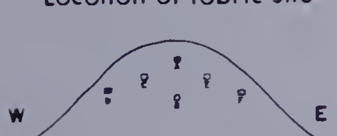


Circles ot one pebble frequency
50 observotions



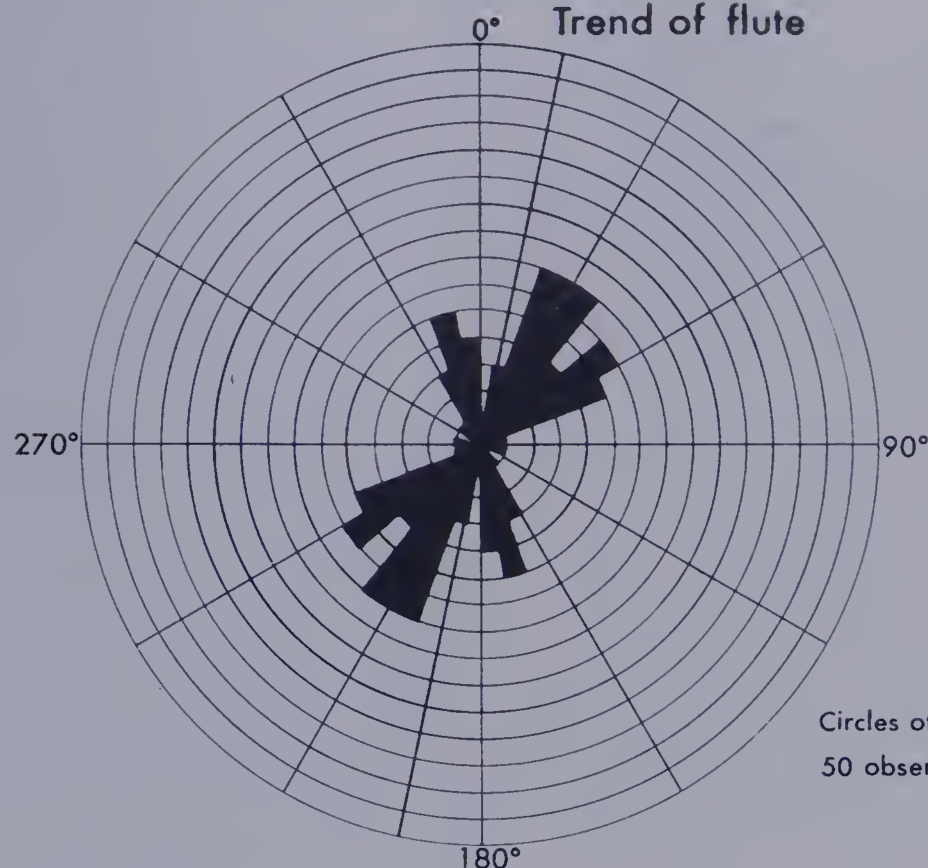
Percentoge of points per 3% oreo
Contour interval 2%

Locotion of fobric site



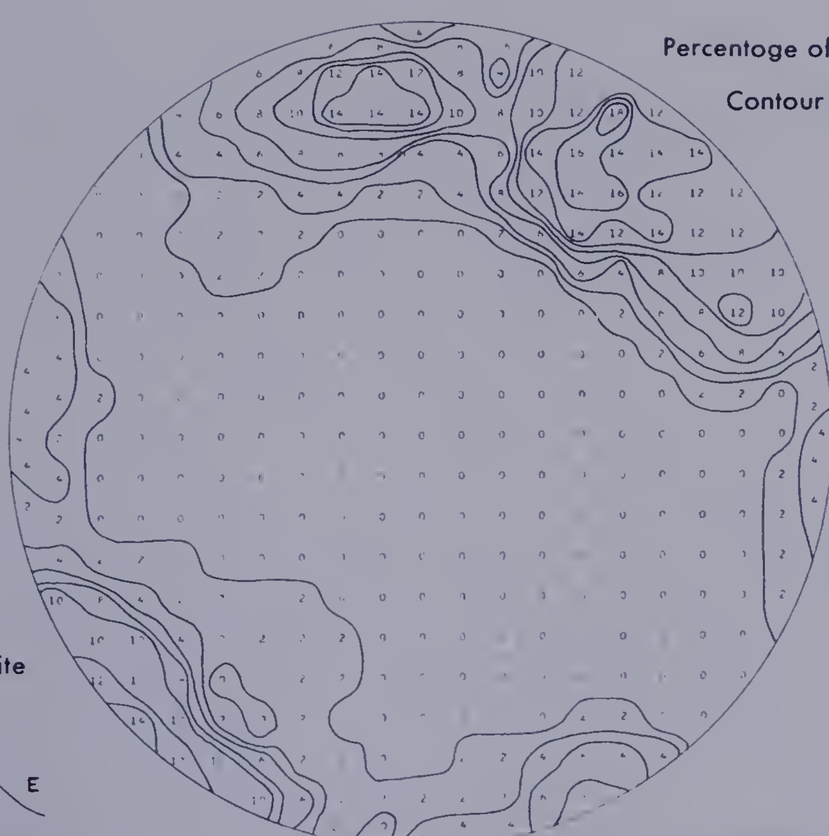
Confidence limit (5%) 18°

Flute 4 Fabric E



Circles of one pebble frequency
50 observations

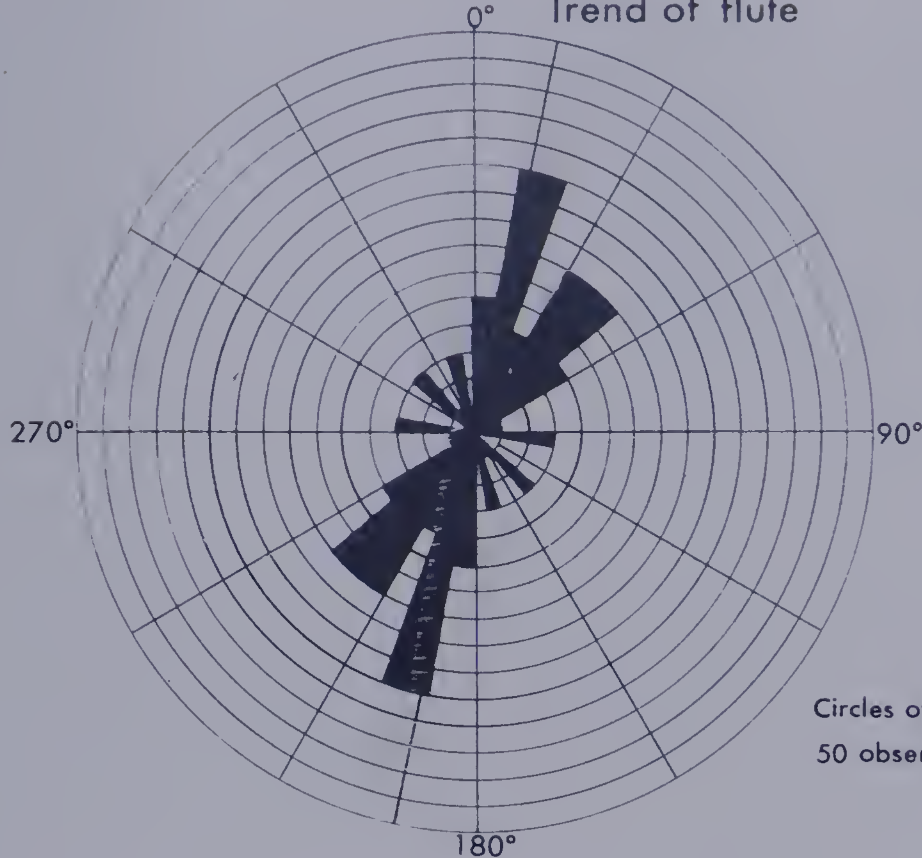
Percentage of points per 3% area
Contour interval 2%

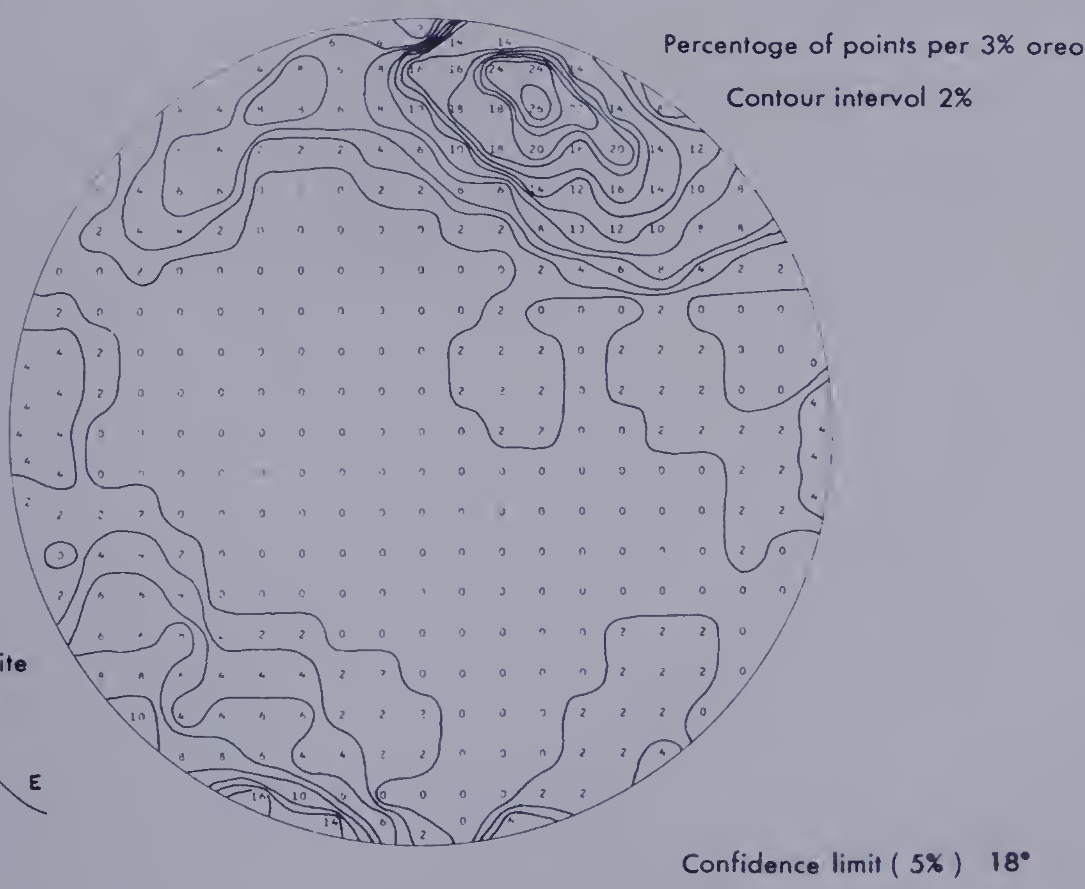


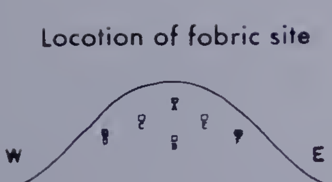
Location of fabric site

Confidence limit (5%) 22°

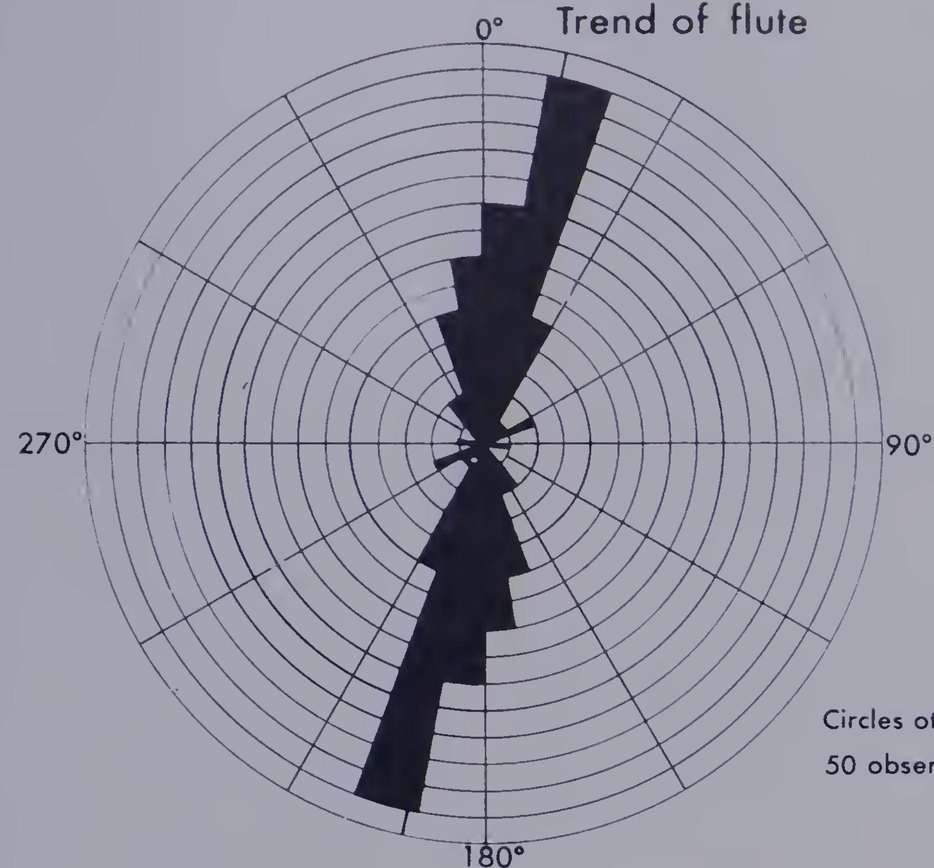
Flute 4 Fabric F



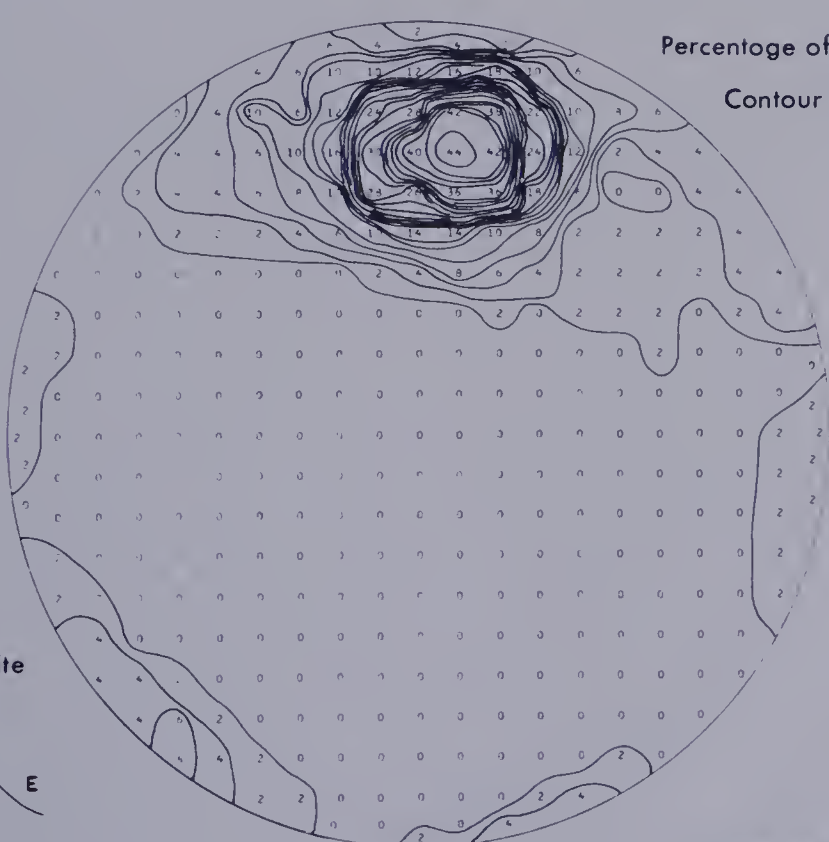




Flute 5 Fabric A

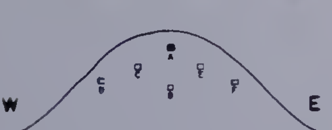


Circles of one pebble frequency
50 observations



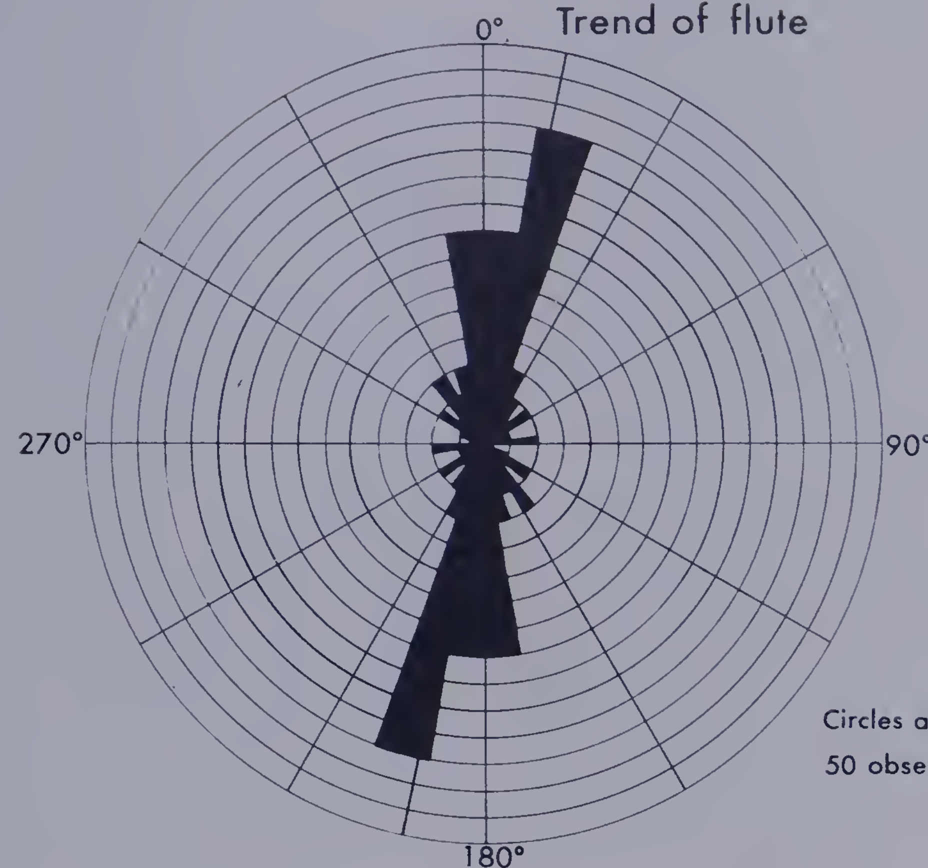
Percentage of points per 3% area
Contour interval 2%

Location of fabric site

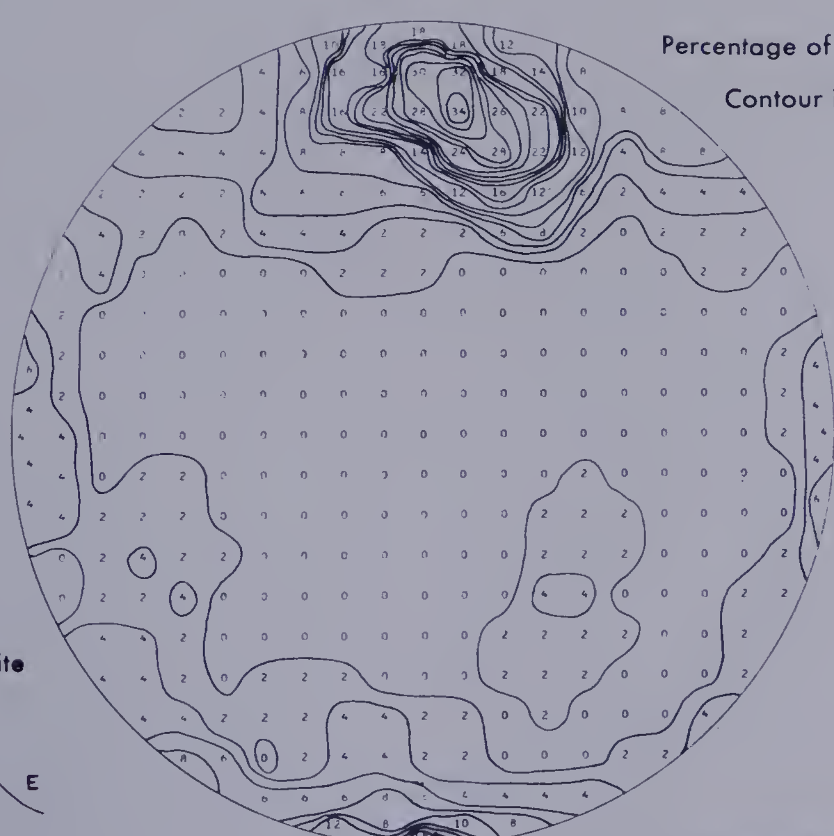


Confidence limit (5%) 10°

Flute 5 Fabric B

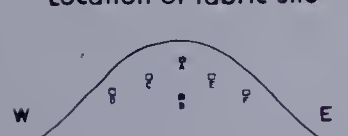


Circles at one pebble frequency
50 observations



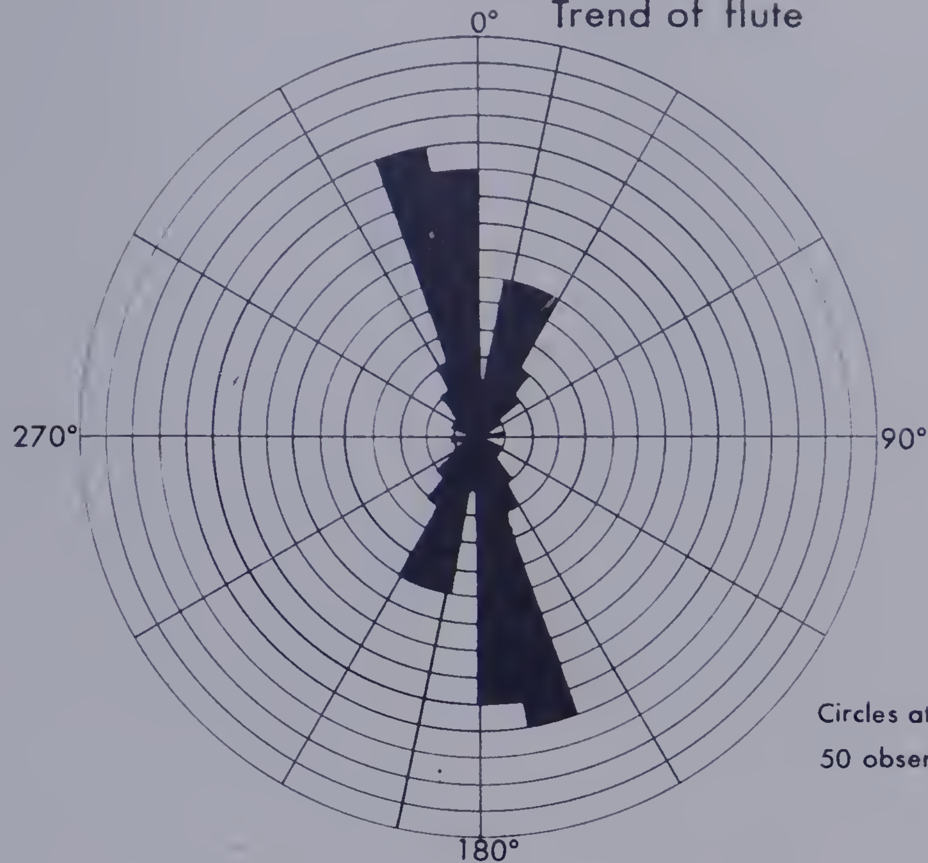
Percentage of points per 3% area
Contour interval 2%

Location of fabric site

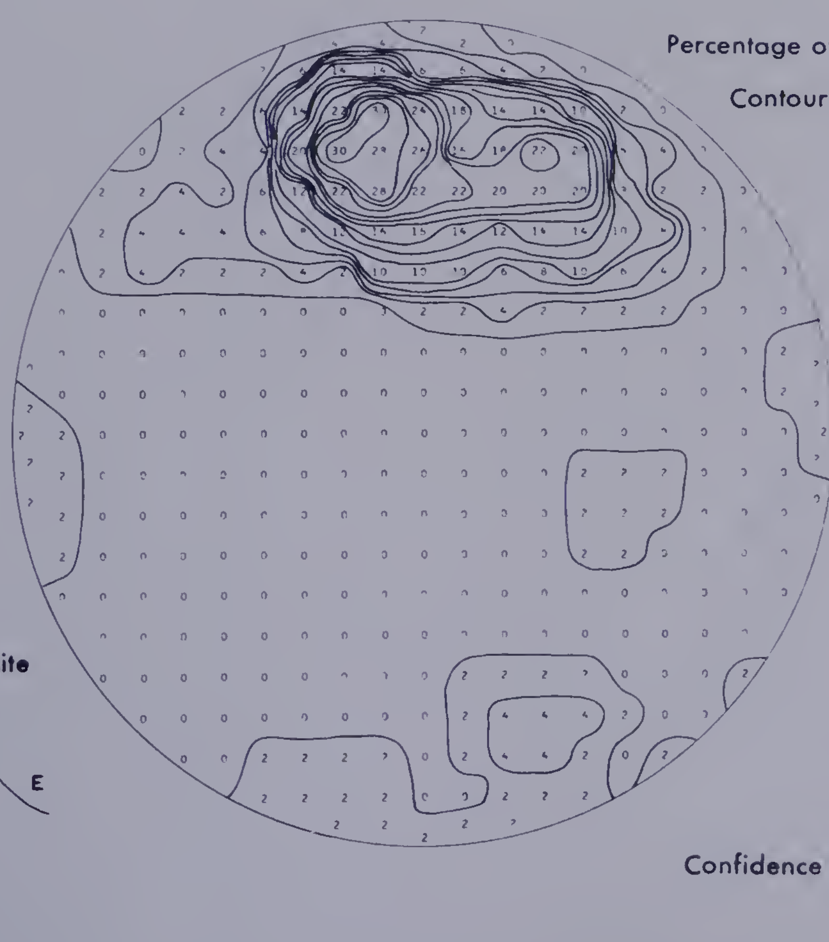


Confidence limit (5%) 16°

Flute 5 Fabric C

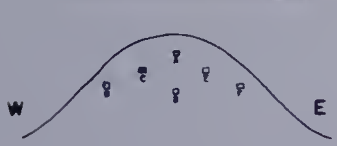


Circles at one pebble frequency
50 observations



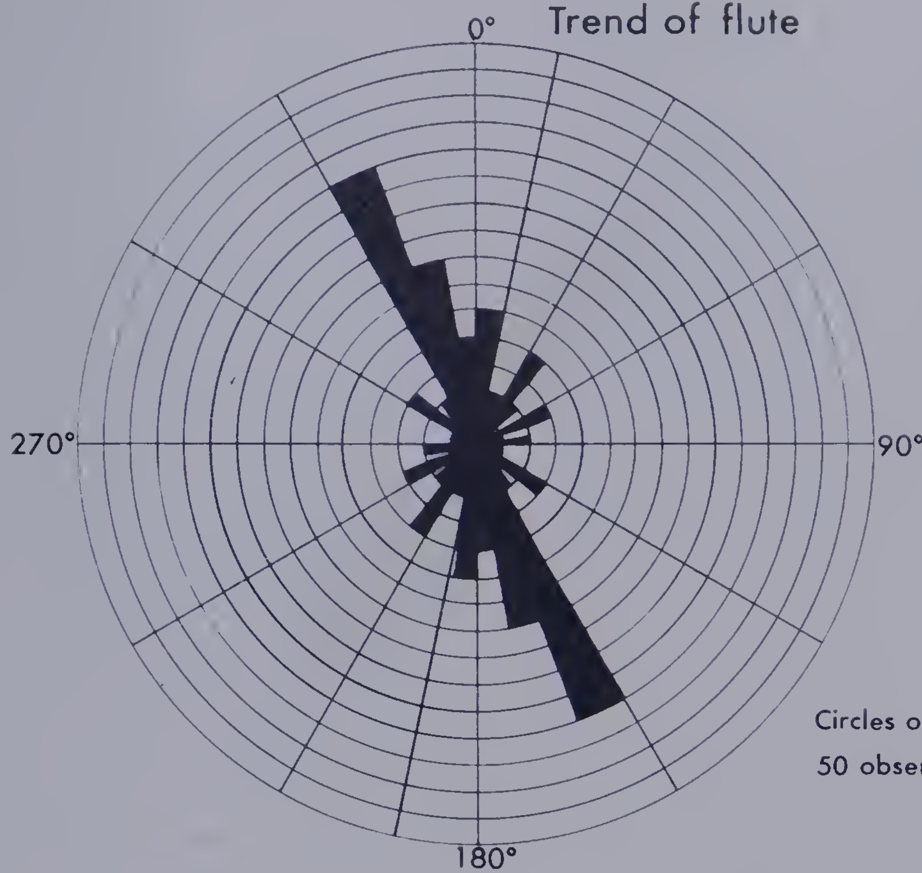
Percentage of points per 3% area
Contour interval 2%

Location of fabric site



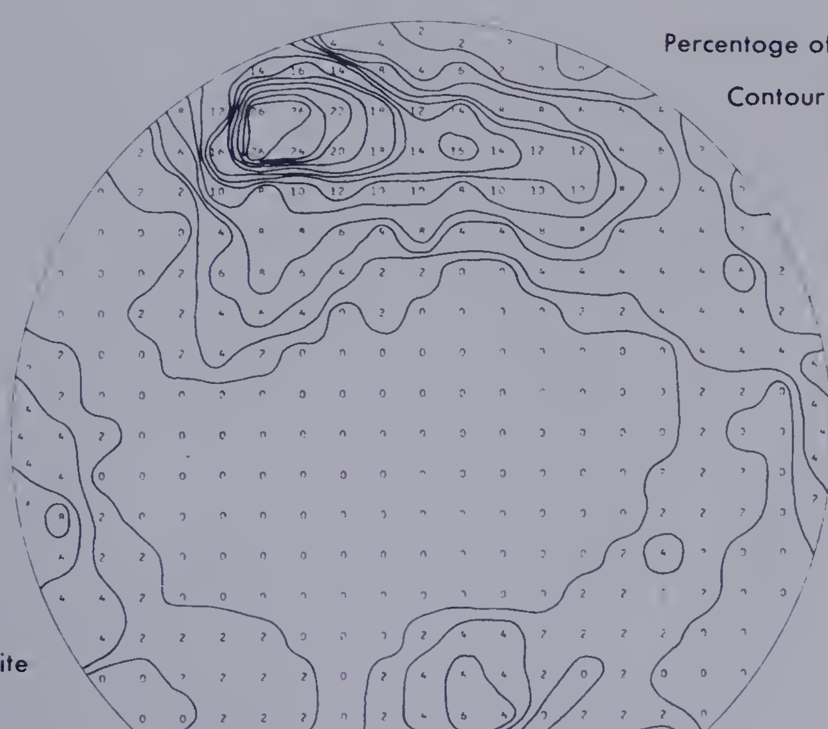
Confidence limit (5%) 11°

Flute 5 Fabric D



Circles at one pebble frequency
50 observations

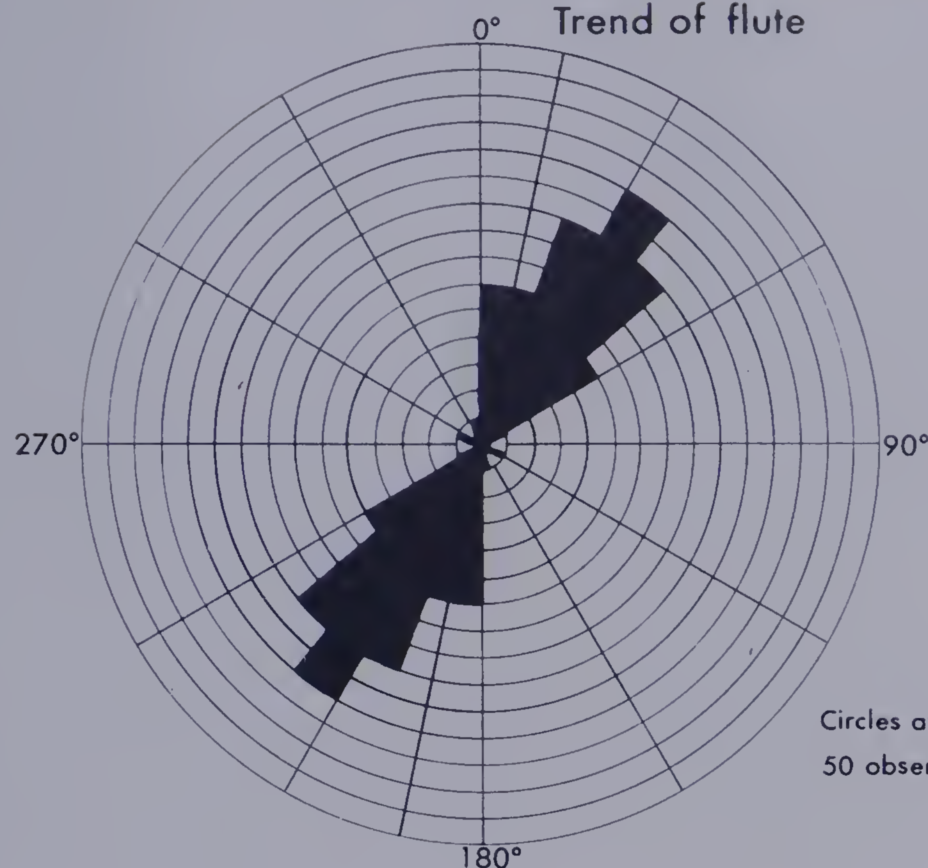
Percentage of points per 3% area
Contour interval 2%



Location of fabric site

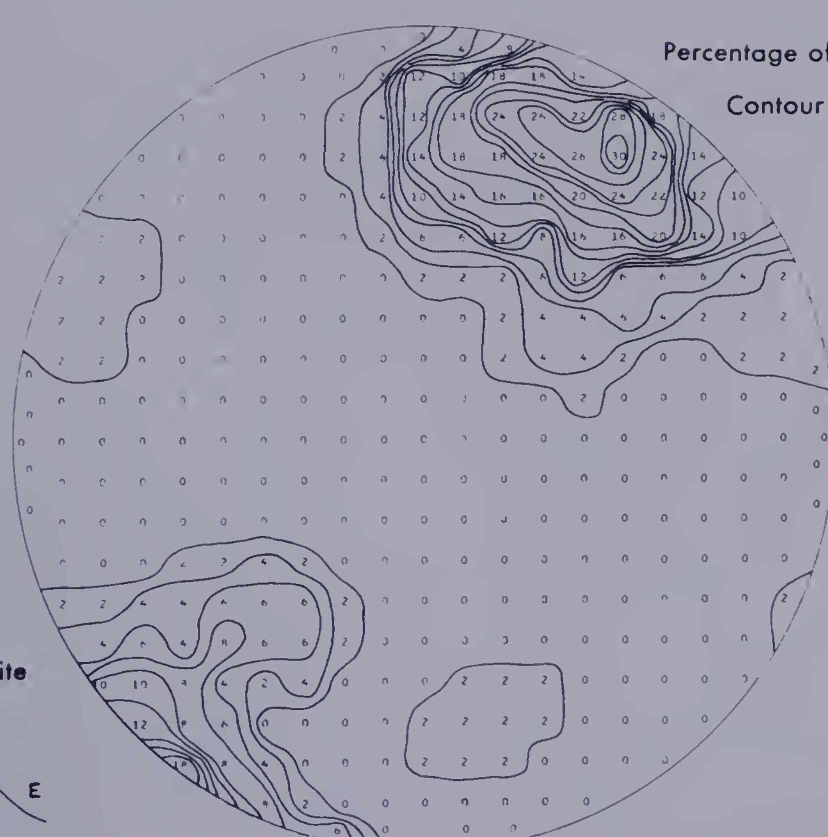
Confidence limit (5%) 17°

Flute 5 Fabric E



Circles at one pebble frequency

50 observations



Percentage of points per 3% area

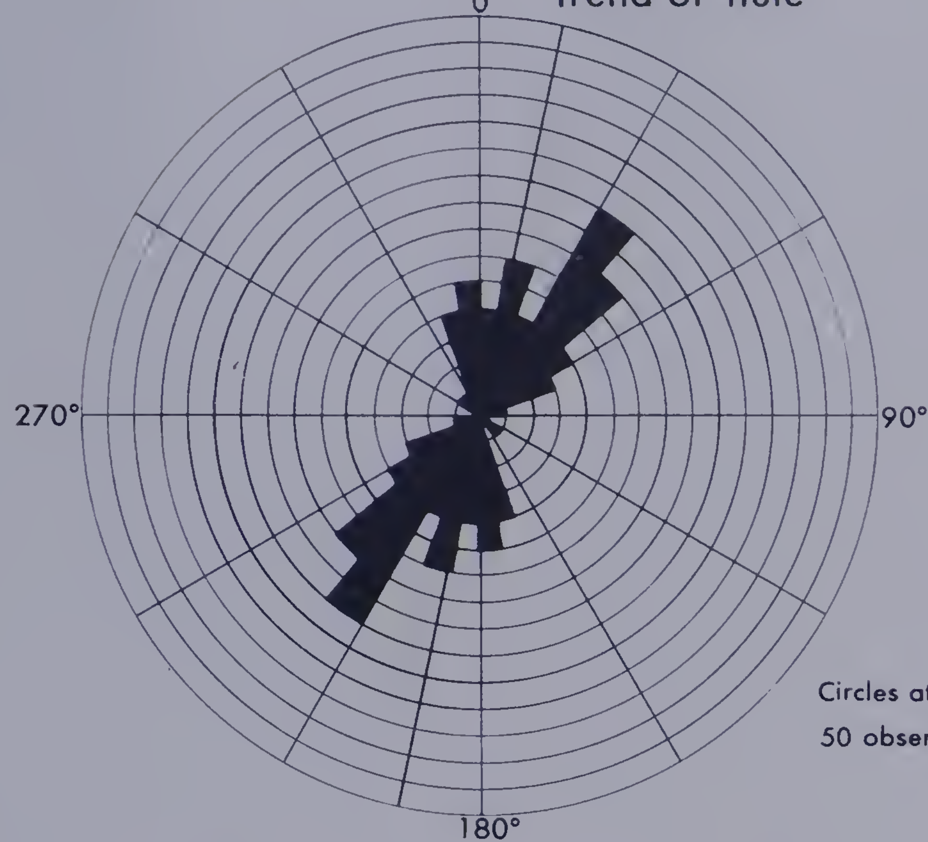
Contour interval 2%

Location of fabric site

Confidence limit (5%) 15°

Flute 5 Fabric F

Trend of flute

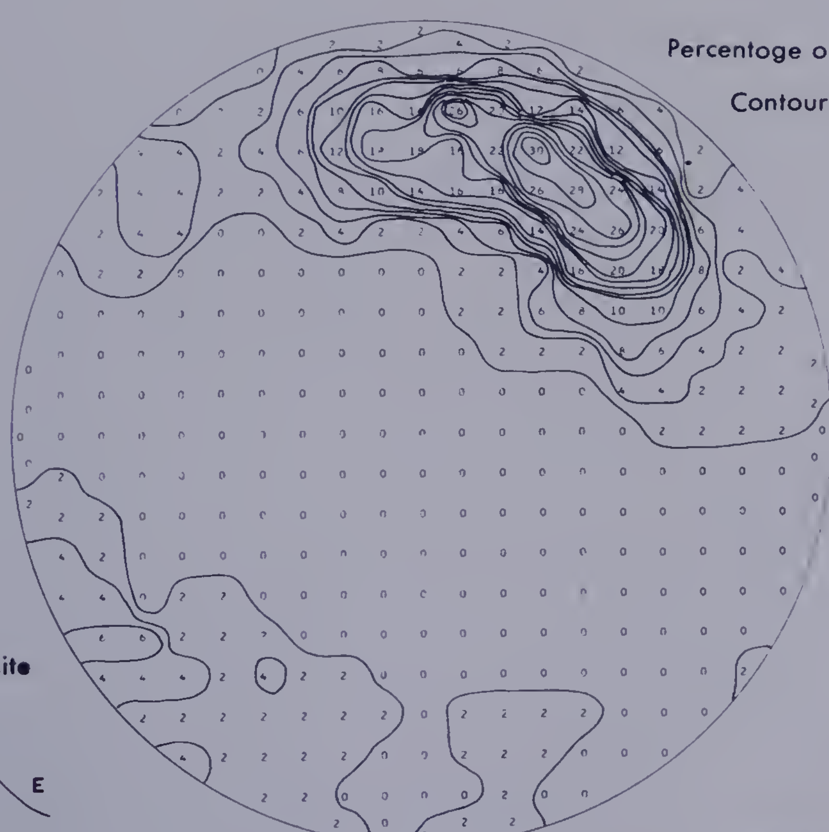


Circles at one pebble frequency

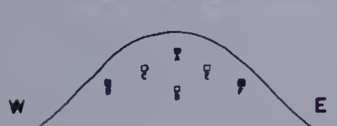
50 observations

Percentoge of points per 3% area

Contour intervol 2%

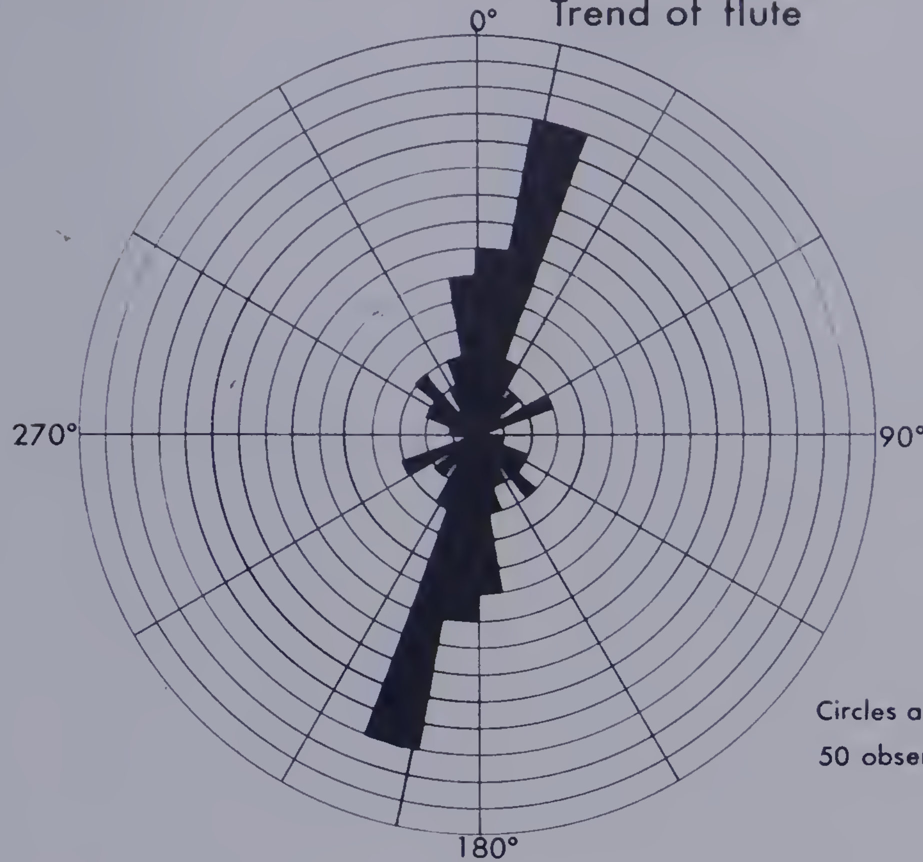


Location of fabric site



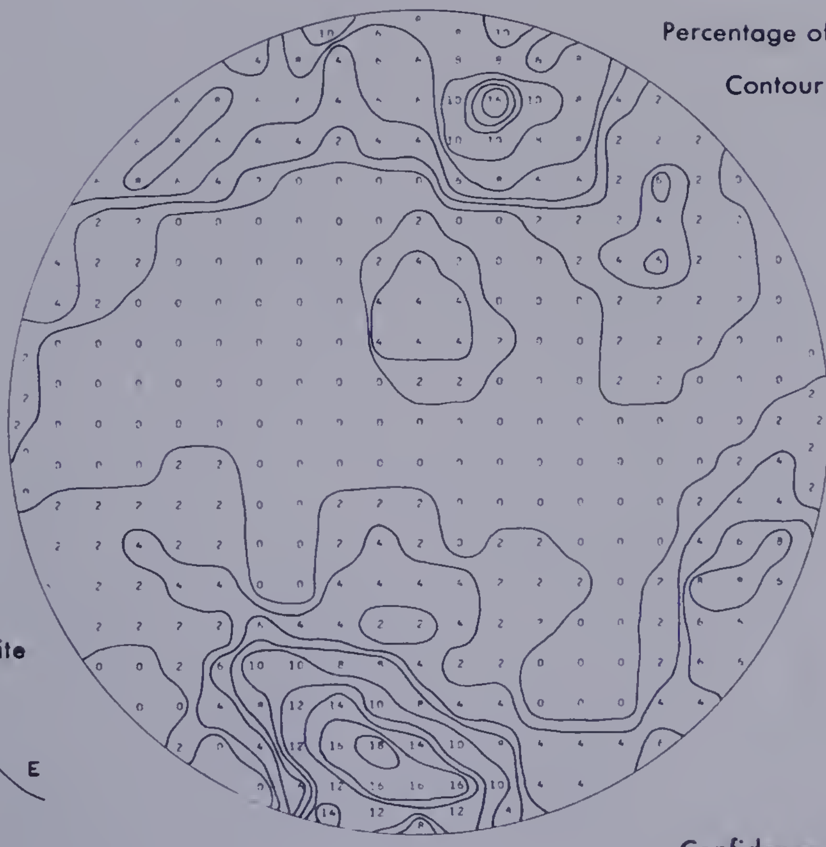
Confidence limit (5%) 14°

Flute 6 Fabric A

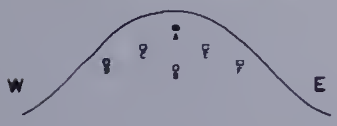


Circles at one pebble frequency
50 observations

Percentage of points per 3% area
Contour interval 2%

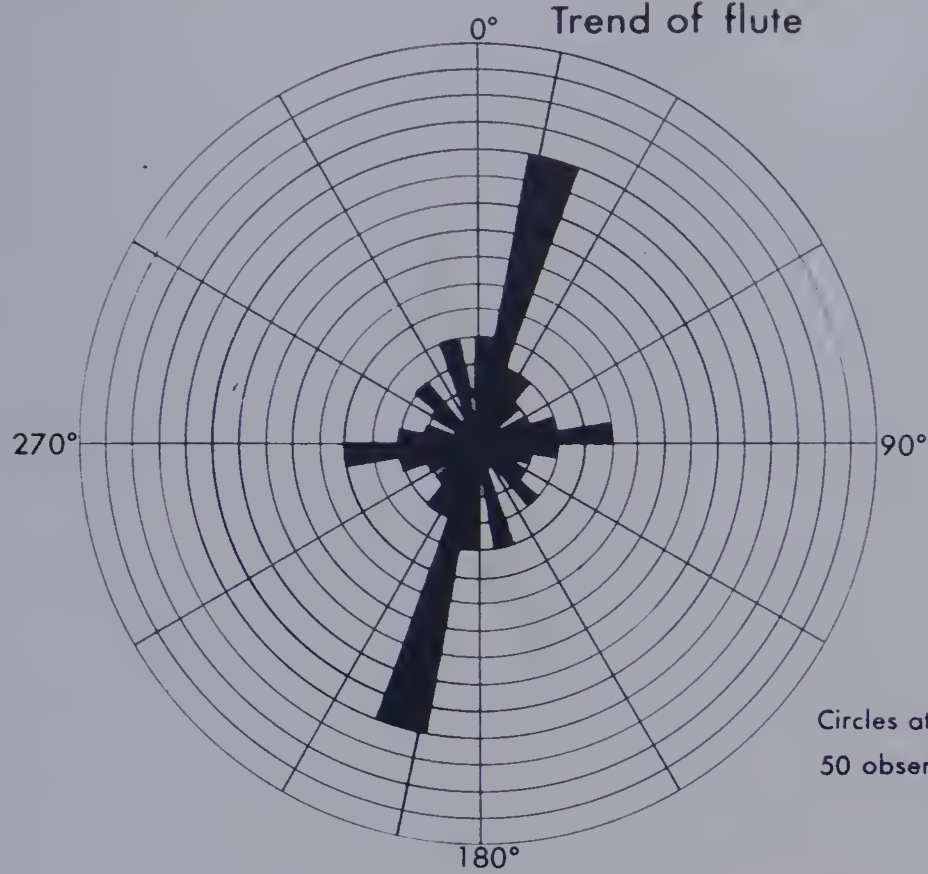


Location of fabric site



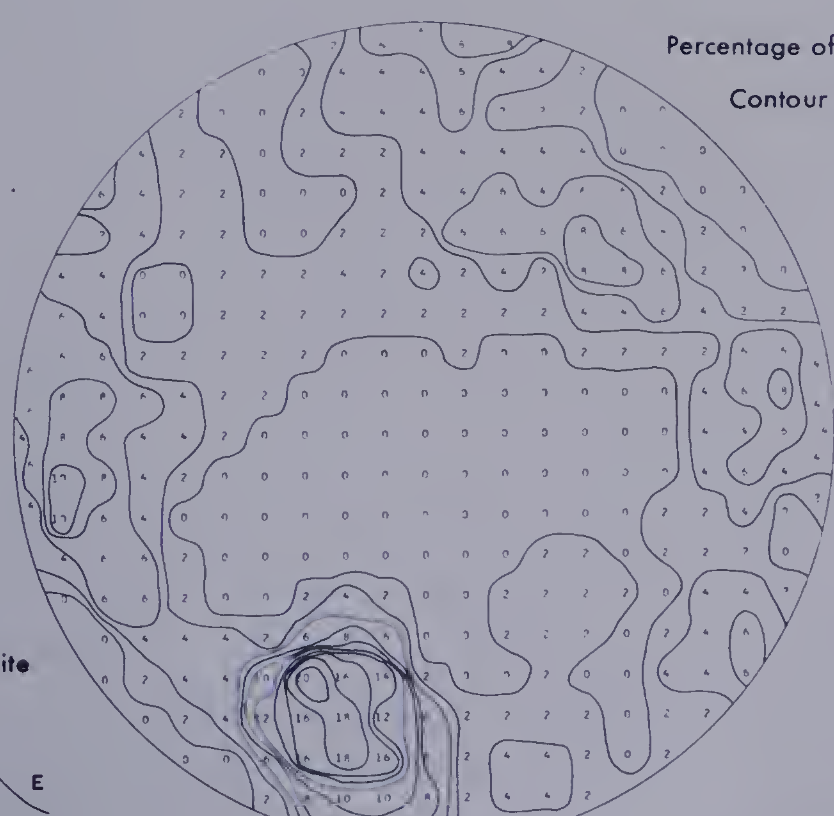
Confidence limit (5%) 27°

Flute 6 Fabric B

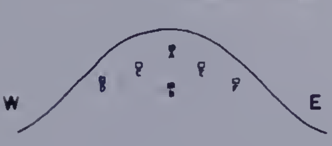


Circles at one pebble frequency
50 observations

Percentage of points per 3% area
Contour interval 2%

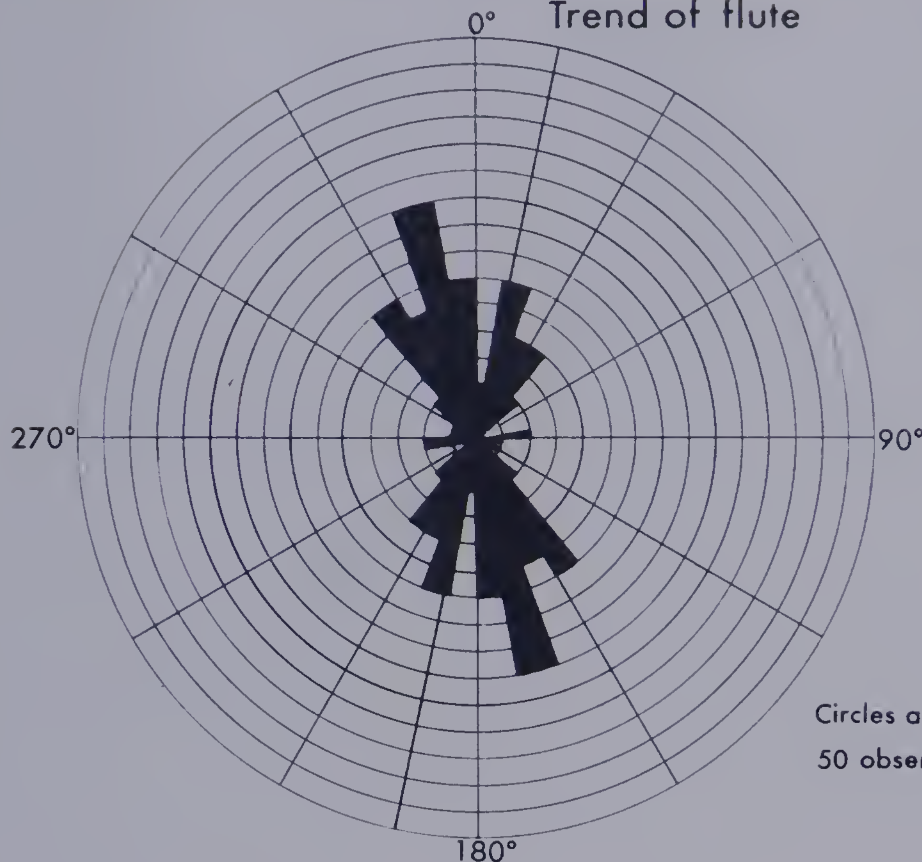


Location of fabric site



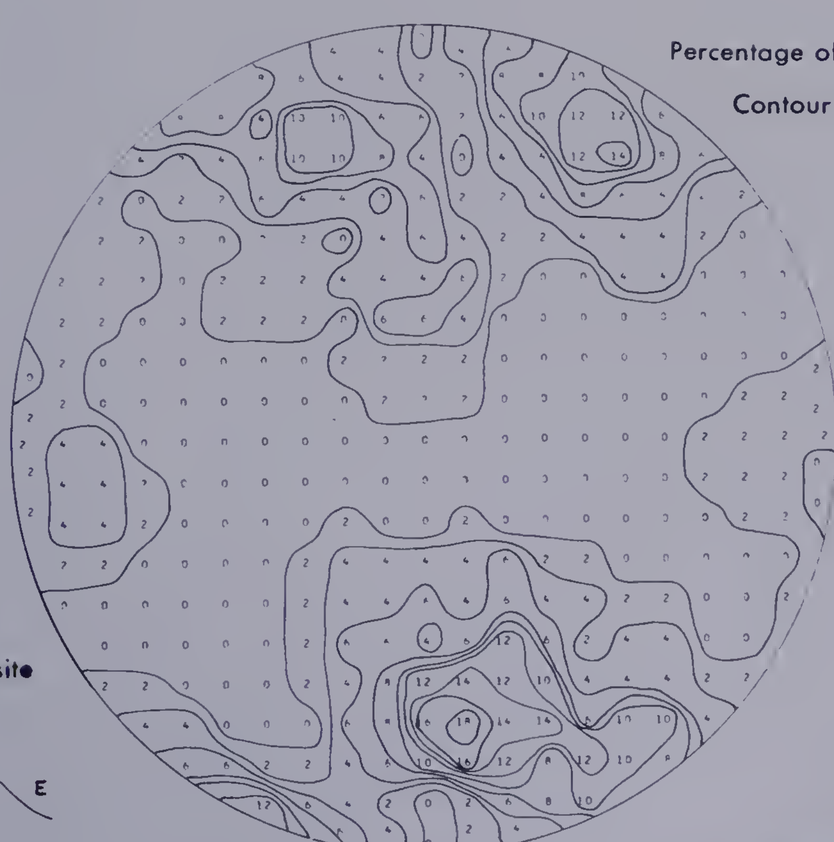
Confidence limit (5%) 24°

Flute 6 Fabric C



Circles at one pebble frequency
50 observotions

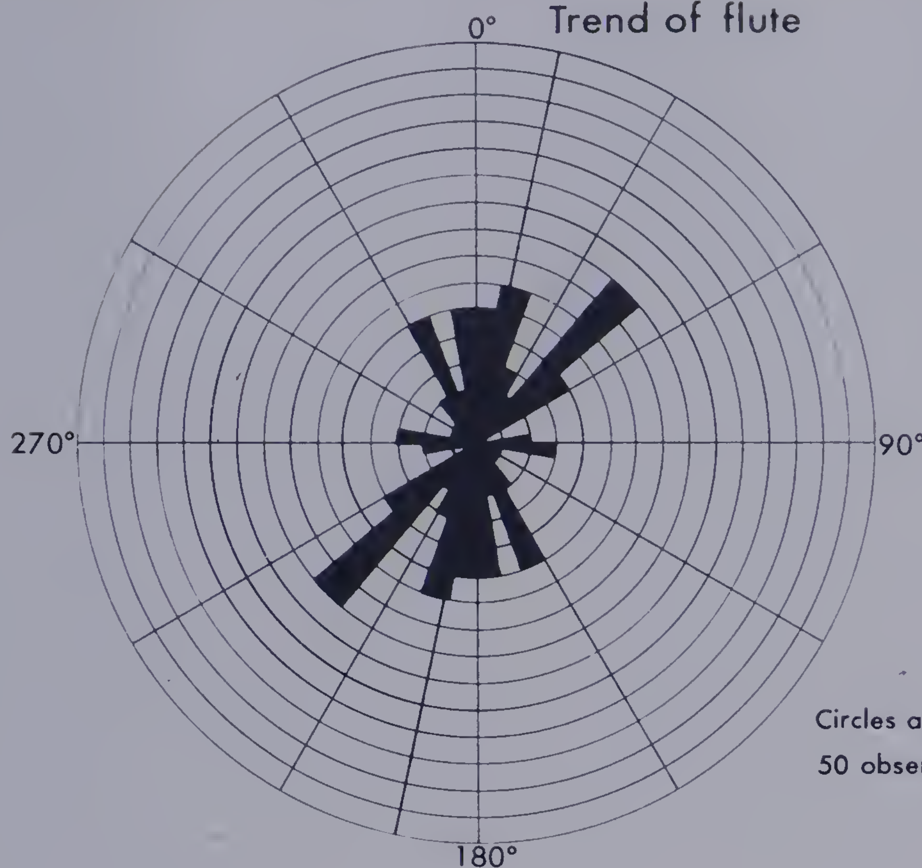
Percentage of points per 3% oreo
Contour interval 2%



Location of fabric site

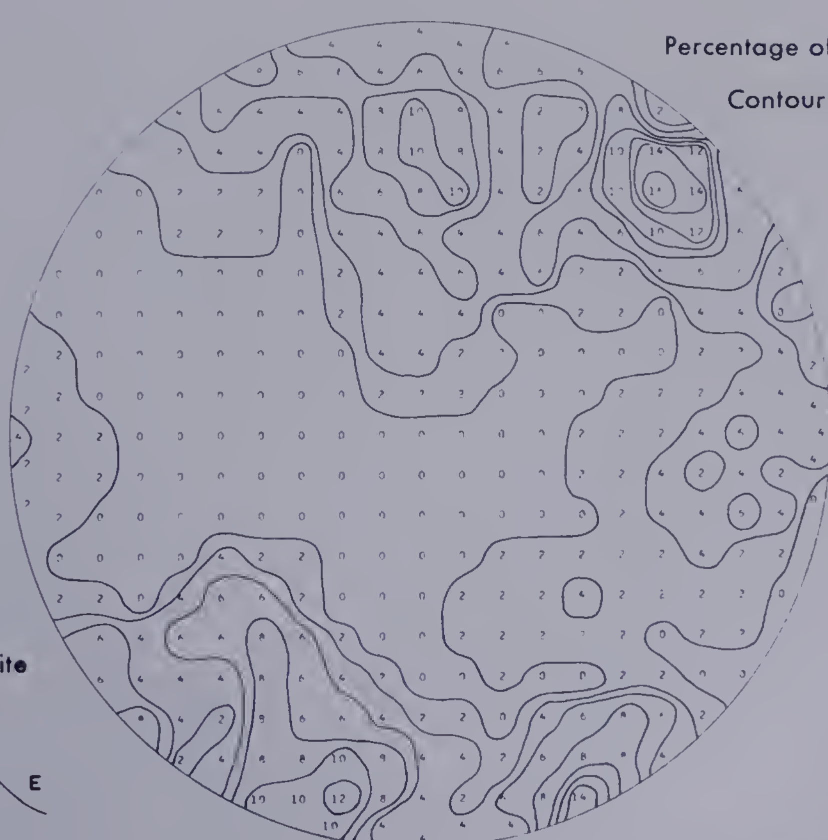
Confidence limit (5%) 23°

Flute 6 Fabric D

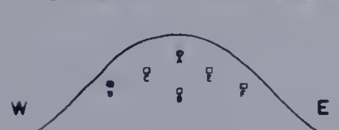


Circles at one pebble frequency
50 observations

Percentage of points per 3% area
Contour interval 2%

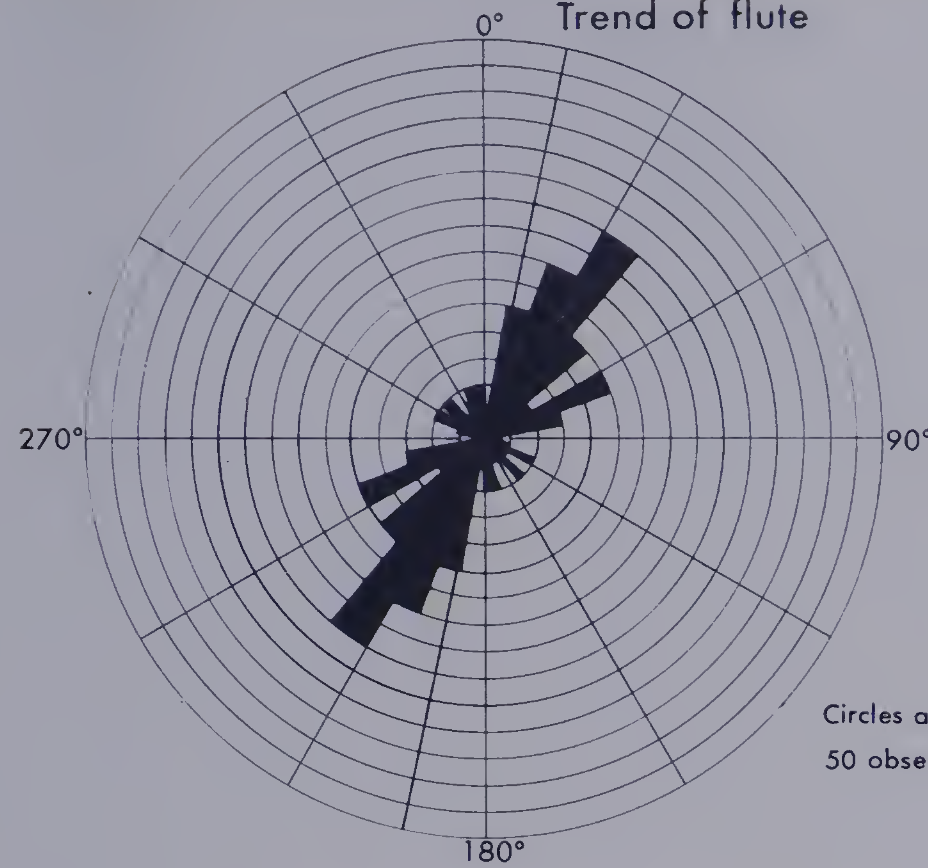


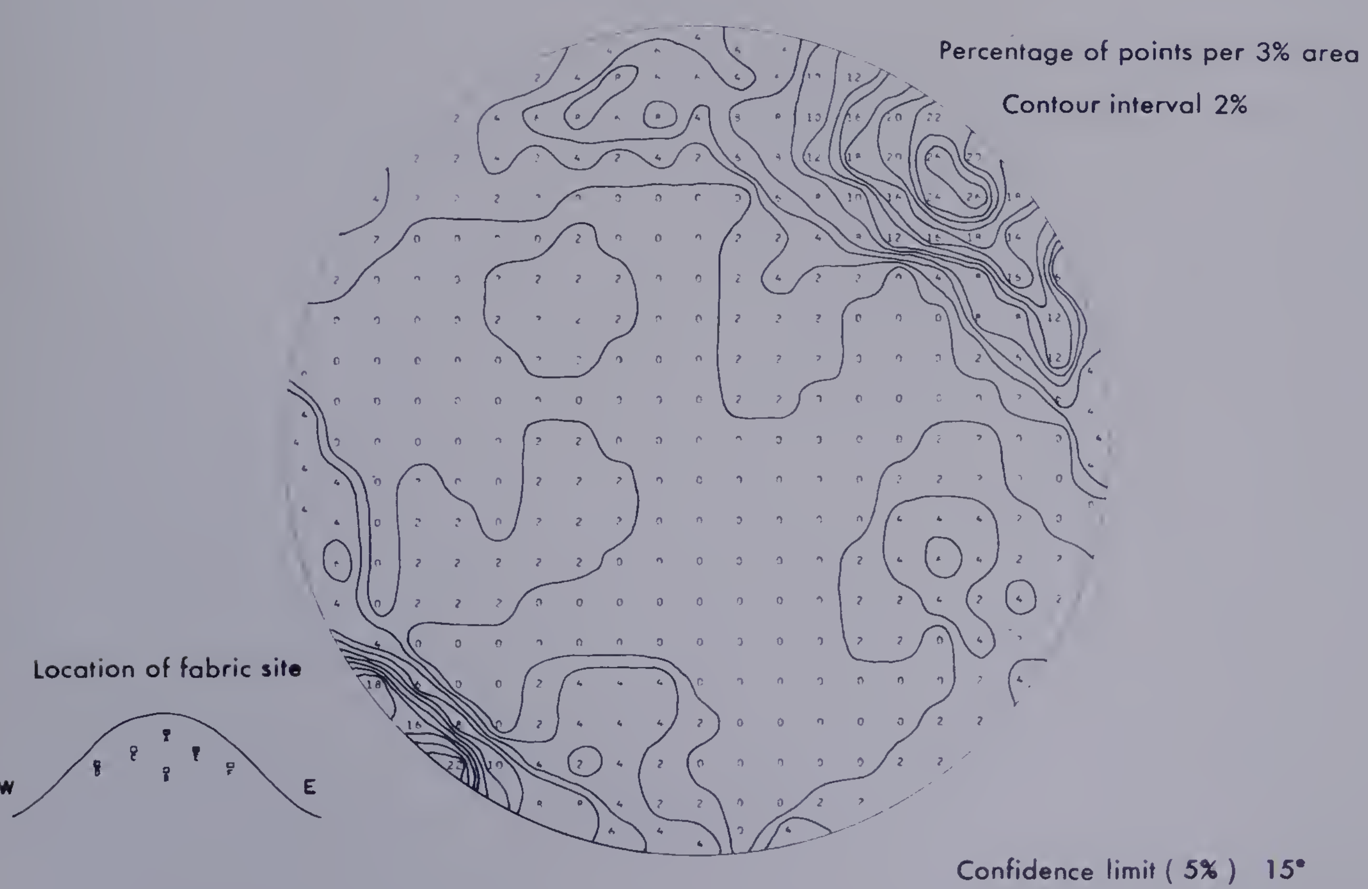
Location of fabric site



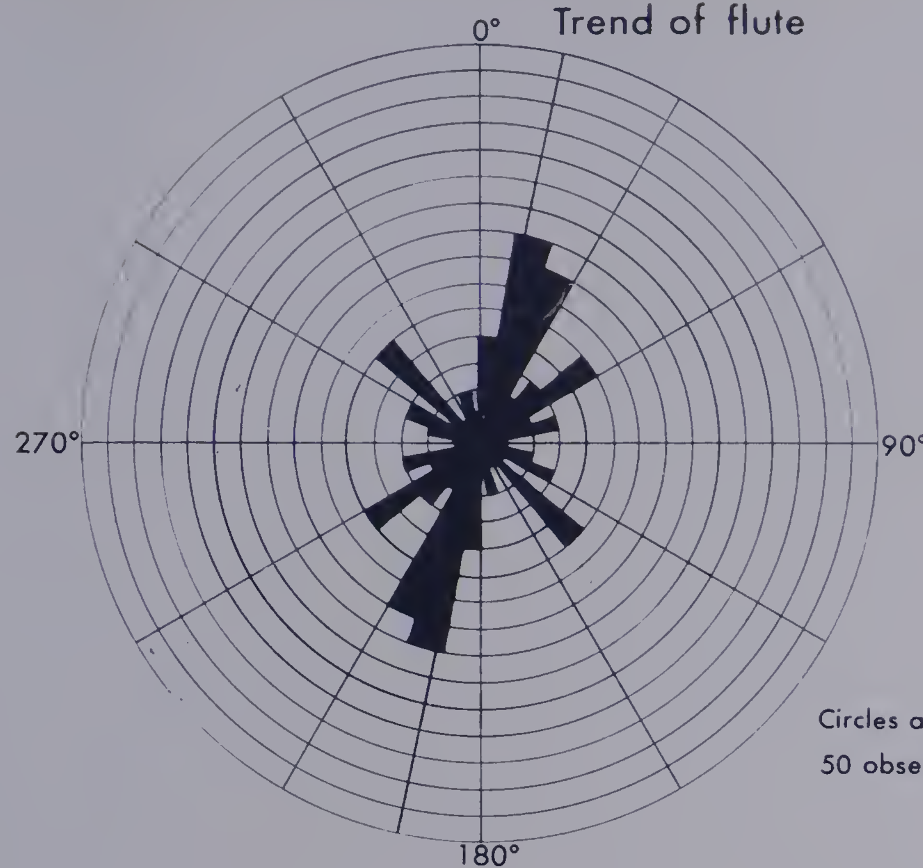
Confidence limit (5%) 26°

Flute 6 Fabric E



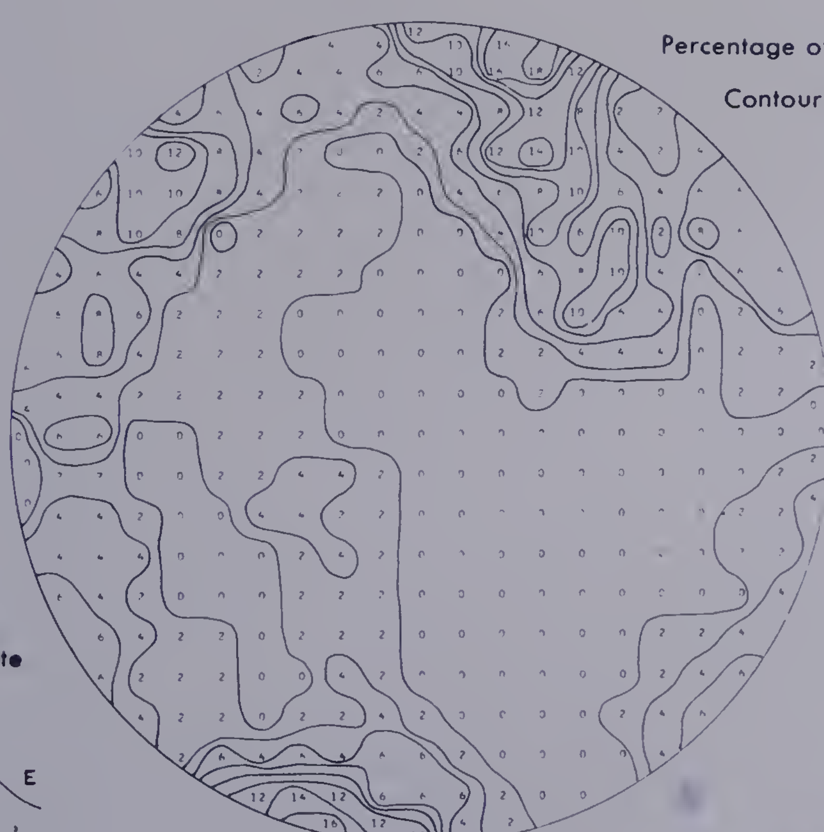


Flute 7 Fabric A

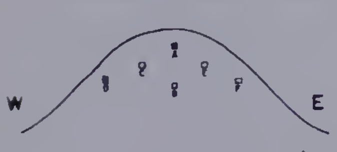


Circles at one pebble frequency
50 observations

Percentage of points per 3% area
Contour interval 2%



Location of fabric site



Confidence limit (5%) 23°